Messengers from the High Energy Universe

What we know

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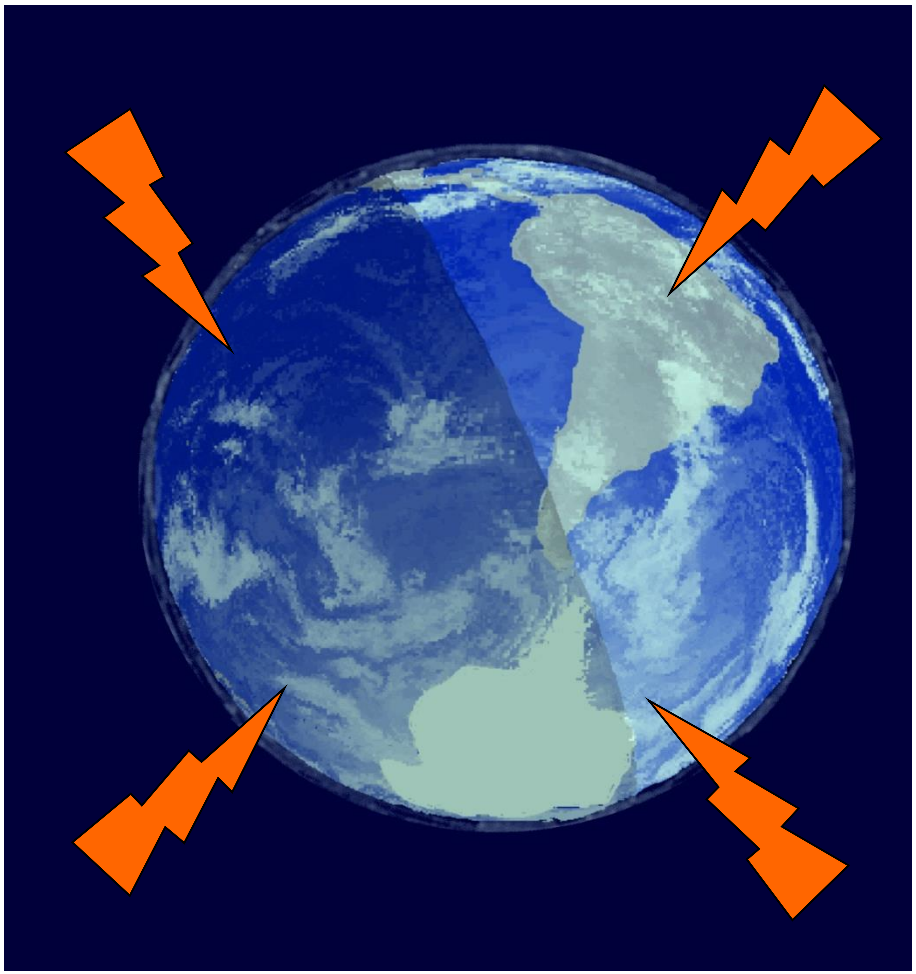
Messengers from the High Energy Universe



Photons

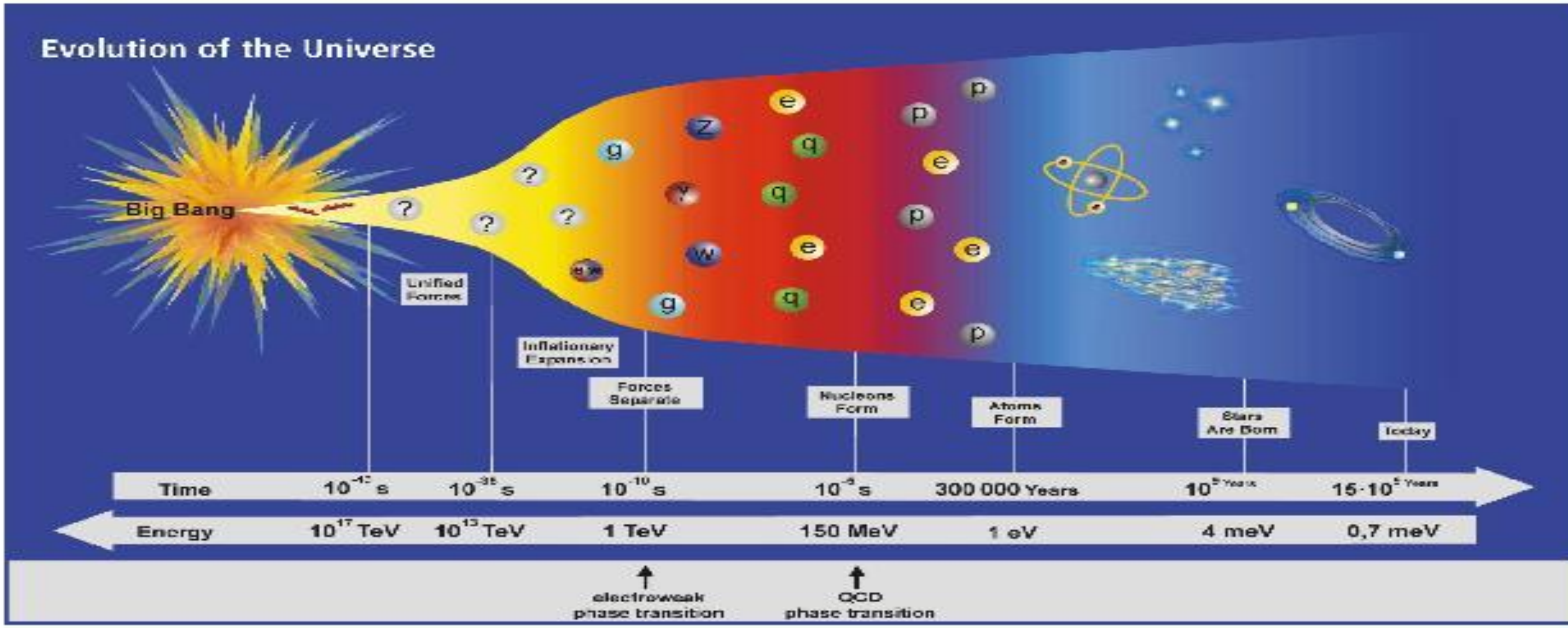
Cosmic rays

Neutrinos

Gravitational Waves

???

The Physics

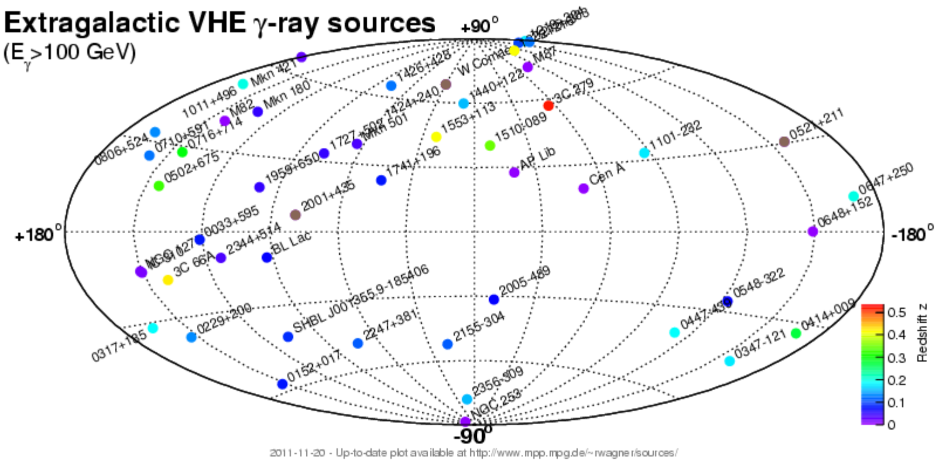

Evolution of the Universe
Big Bang
Unified Forces
Inflationary Expansion
Forces Separate
Nucleons Form
Atoms Form
Stars Are Born
Today
Time
300 000 Years
Energy
10^{17} TeV
10^{13} TeV
1 TeV
150 MeV
1 eV
4 meV
0,7 meV
electroweak phase transition
QCD phase transition

The Physics (γ, p/nucleus, ν , ? beams)

Astrophysics

Sources:AGNs, Pulsares, GRBs, SNRs…

Aceleration mechanisms, propagation



γ sky > 100 GeV
Nov 2011

Particle Physics

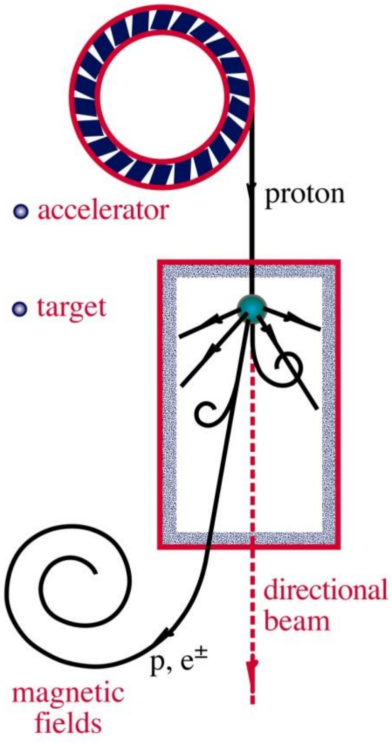
High Energies

$\sqrt{s} \sim 100 - 400$ TeV

Low fluxes

Limited kinematic region

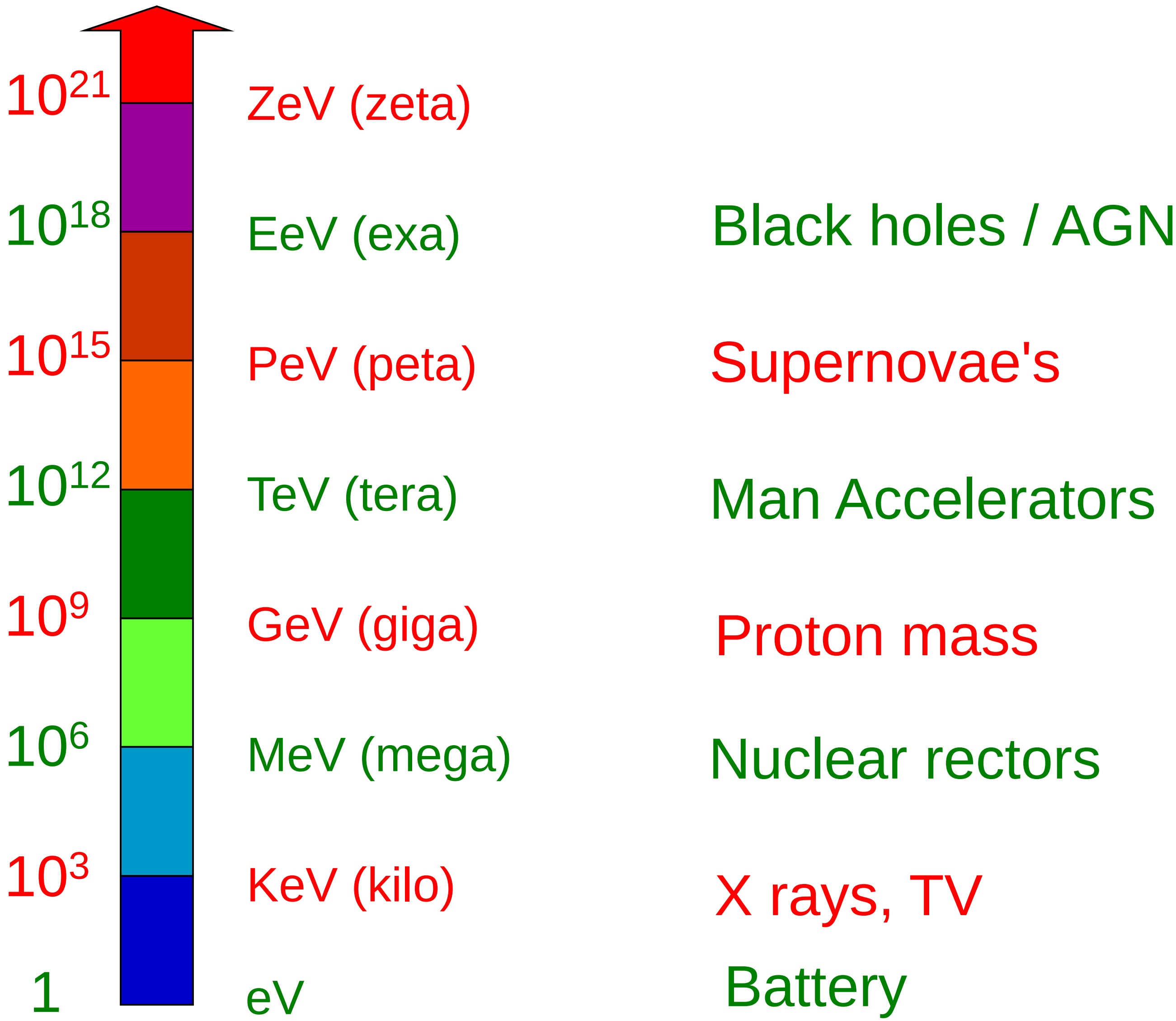
Poor detection capabilities

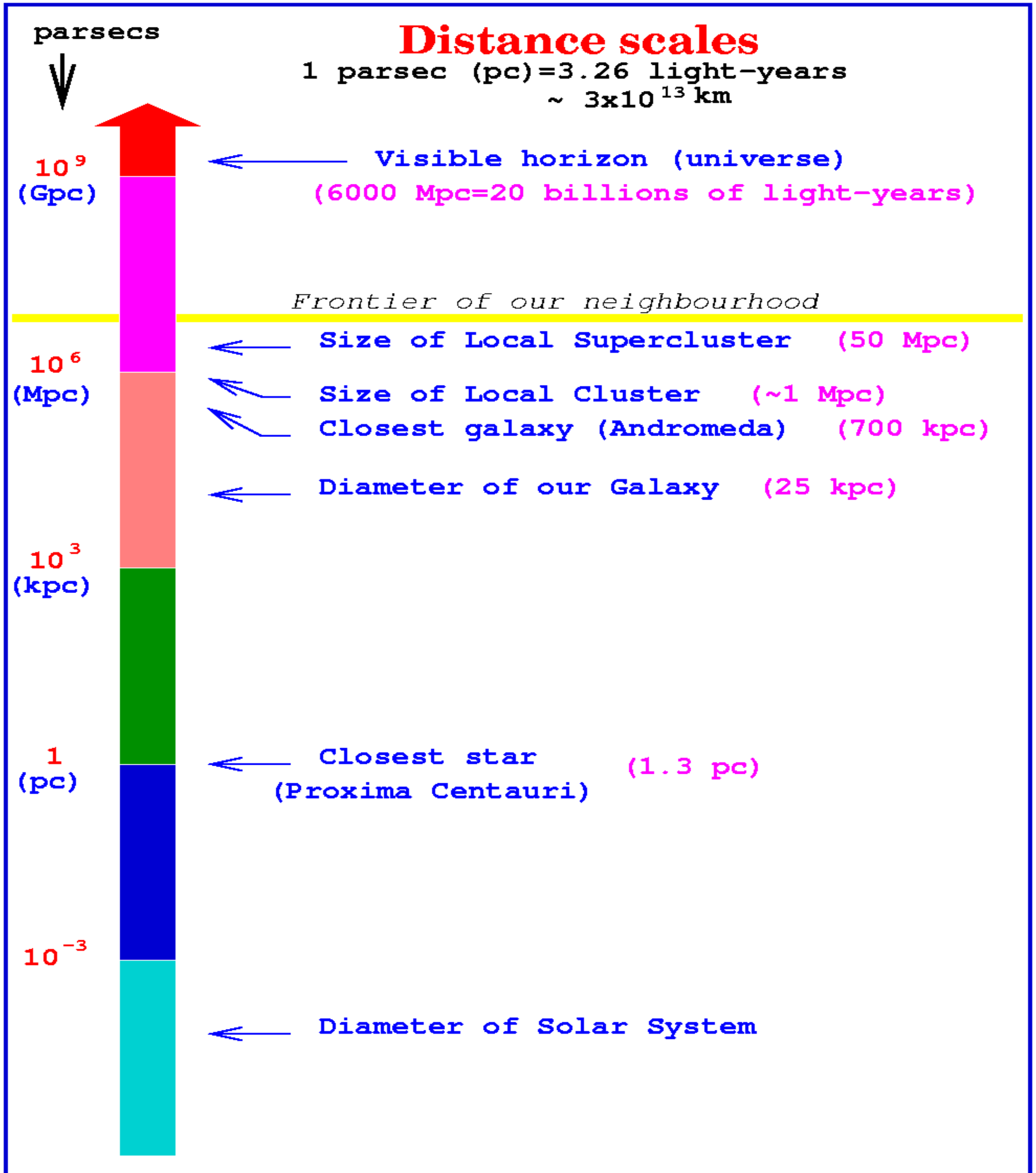


Cosmology/Fundamental Physics

Lorentz symmetry violation, extra-dimensions, dark matter, dark energy …

Energy scales



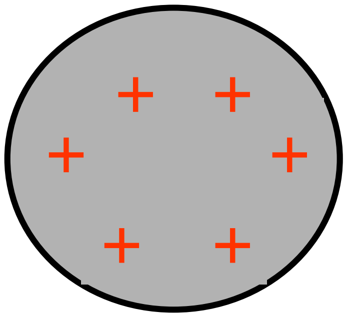


Distance scales
1 parsec (pc)=3.26 light-years
~ 3x10 13 km
parsecs
10 9
(Gpc)
Visible horizon (universe)
(6000 Mpc=20 billions of light-years)
Frontier of our neighbourhood
10 6
(Mpc)
Size of Local Supercluster (50 Mpc)
Size of Local Cluster (~1 Mpc)
Closest galaxy (Andromeda) (700 kpc)
Diameter of our Galaxy (25 kpc)
10 3
(kpc)
1
(pc)
Closest star
(Proxima Centauri)
(1.3 pc)
10 -3
Diameter of Solar System

The beginnings

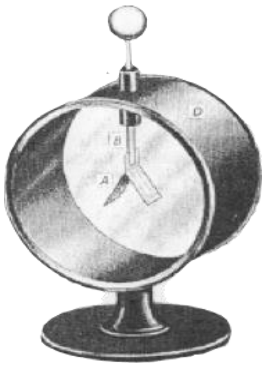
Free electrical charges in the atmosphere !!!

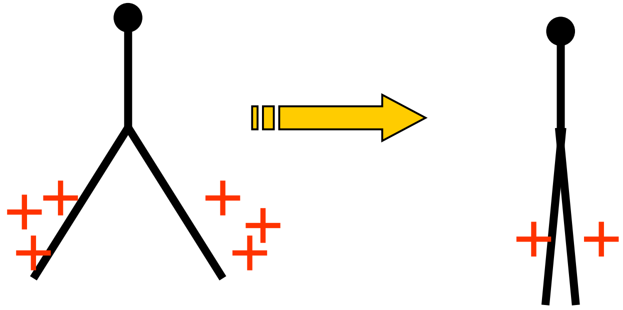
Coulomb, 1785



Discharge of charged conductors ...

End of XIX century

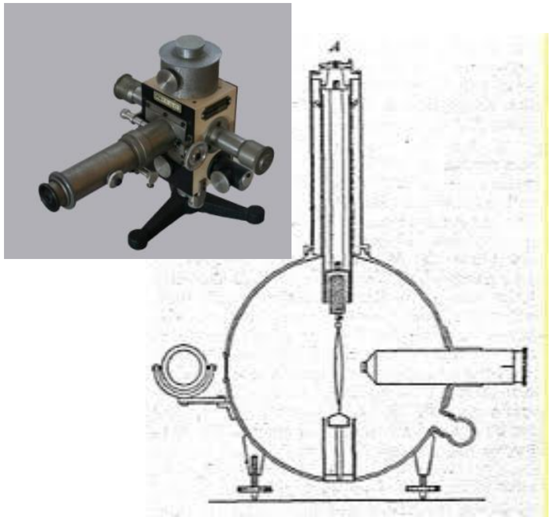




Radioactivity ?

Make good electroscopes!

The two friends Julius Elster and Hans Geiter, gymnasium teachers in Wolfenbuttel, around 1900

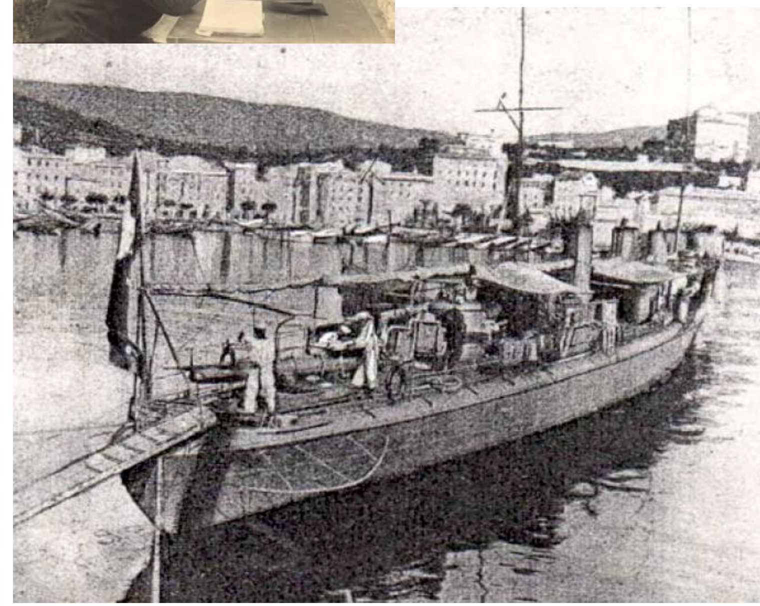


Theodor Wulf, German Jesuit, perfected the electroscope in 1908-09, up to a sensitivity of 1 volt

By sea and by sky

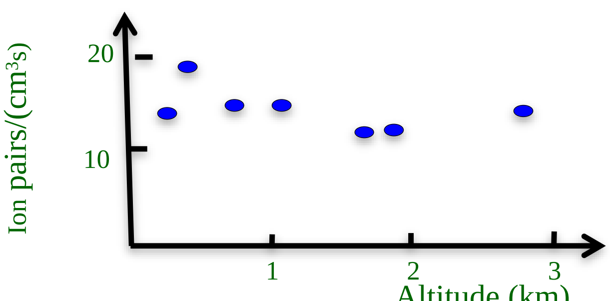
Wulf 1909-
1910

Gockel 1909



Domenico
Pacini1911

Results
not
conclusive



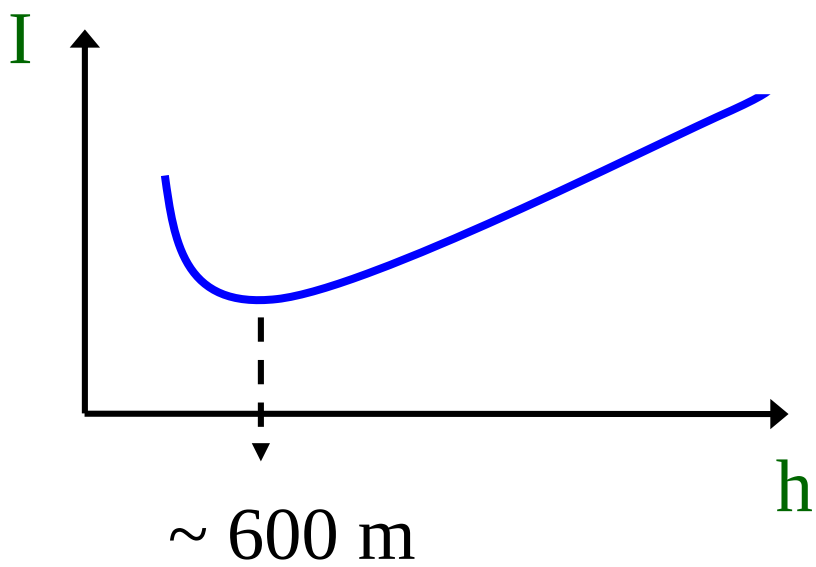
the winning idea !!!: immersing an electroscope 3m deep in the sea
Pacini finds a significant (20% at 4.3σ) reduction

The radiation comes from the sky!!!

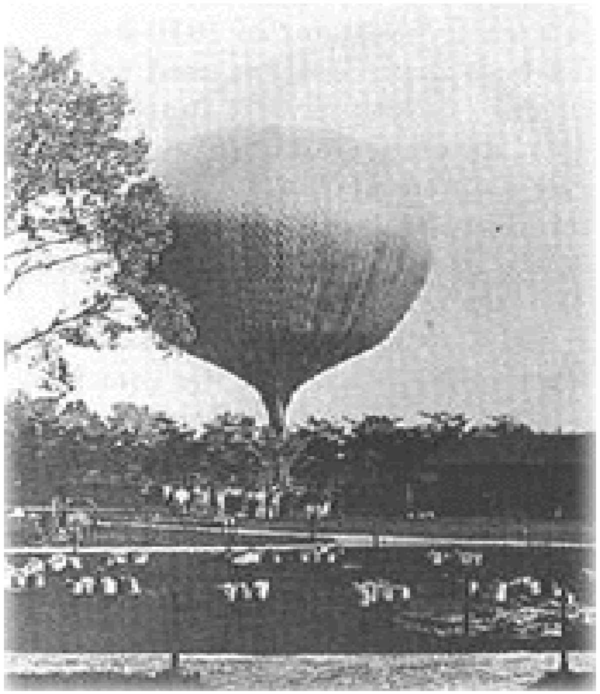
Viktor Hess, 1912

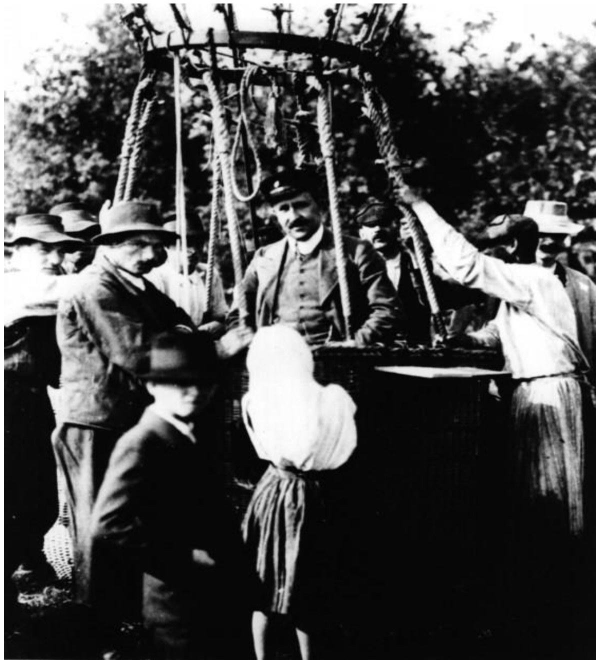
Several flights up to 6 Km

Day/night, eclipses, ...

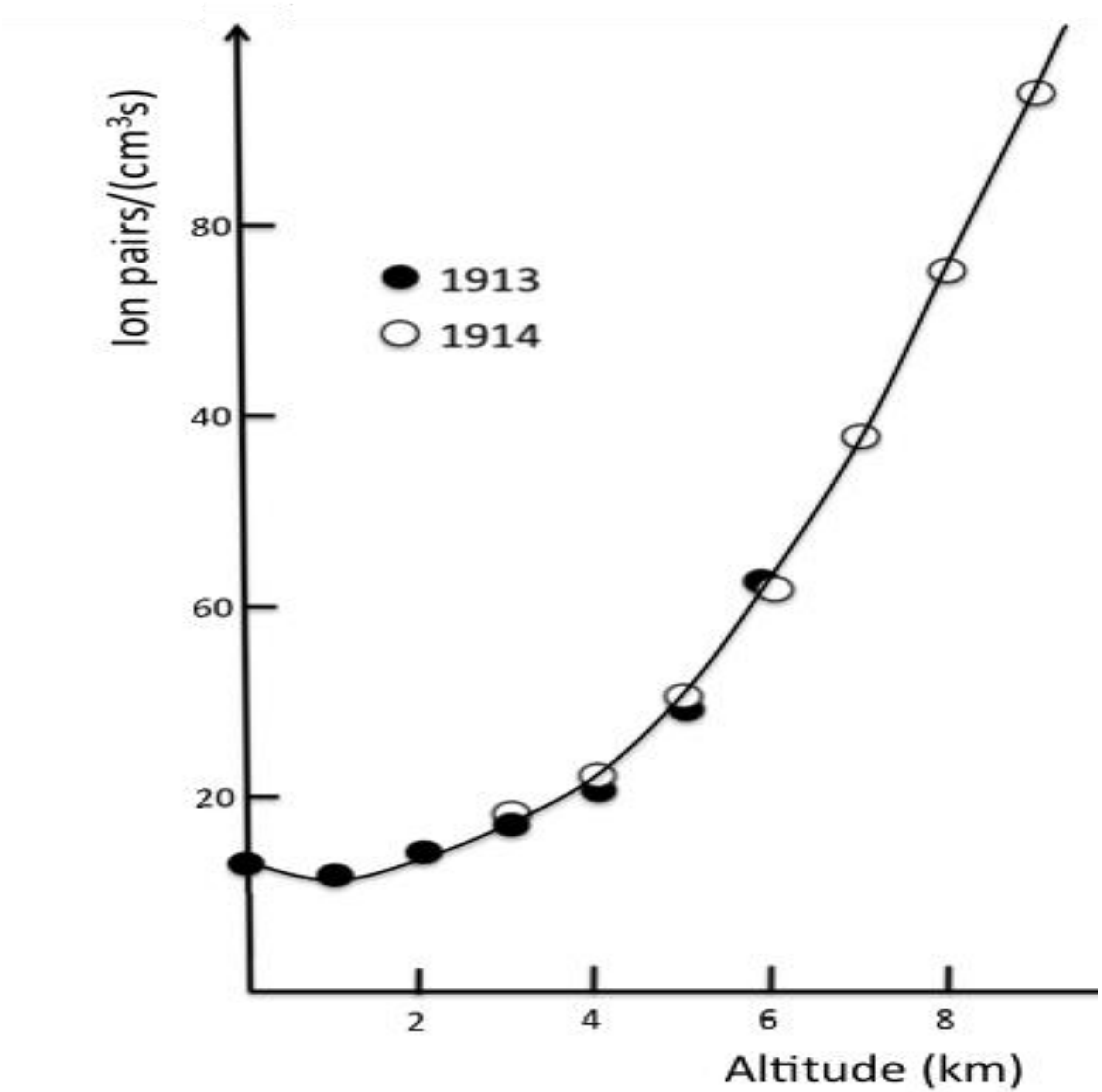


"Cosmic Rays" ! (Milikan)





The confirmation



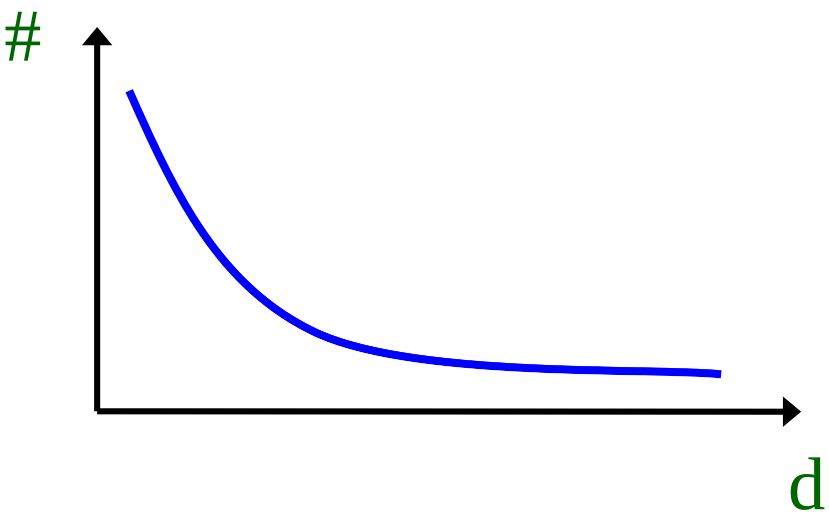
Kolhörster

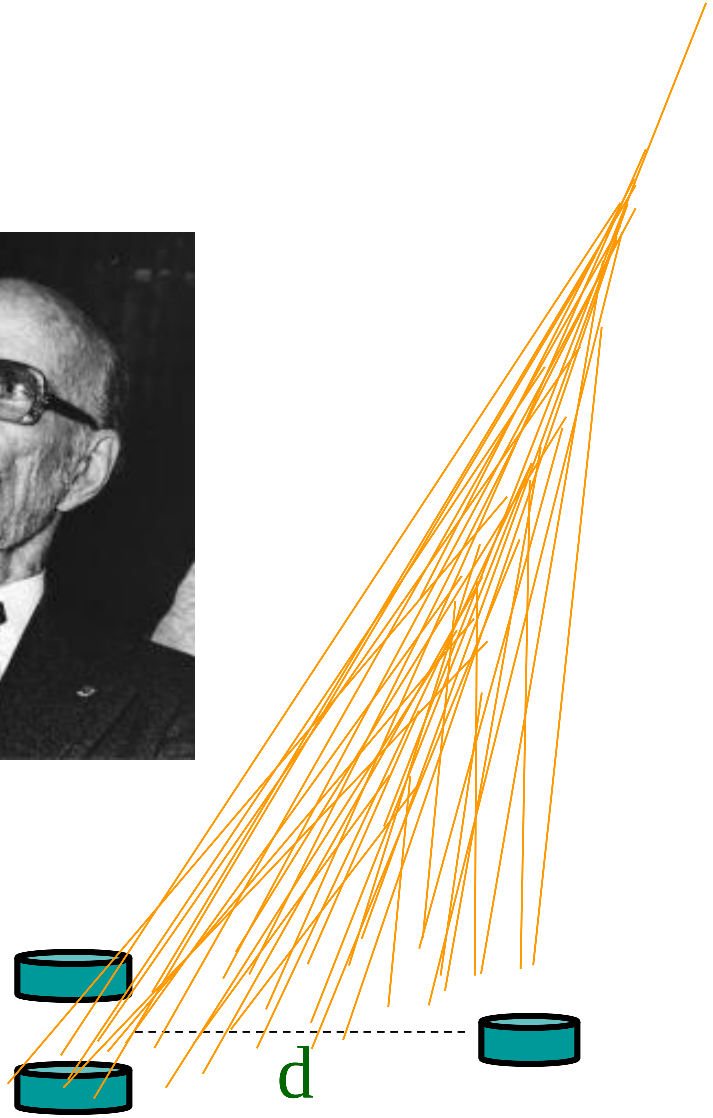
Flights up to 9200 m !!!

Particle showers

Pierre Auger, 1938

Coincidences





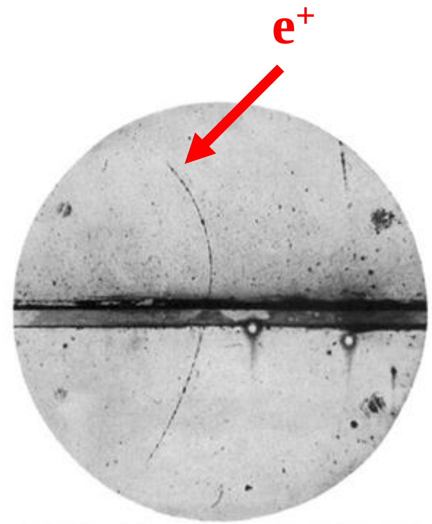
First shower energy estimates !

Particle Physics Birth

Positron (Anderson1932)

Antimatter! (Dirac)

$\gamma \rightarrow e^+e^-$ (Einstein)

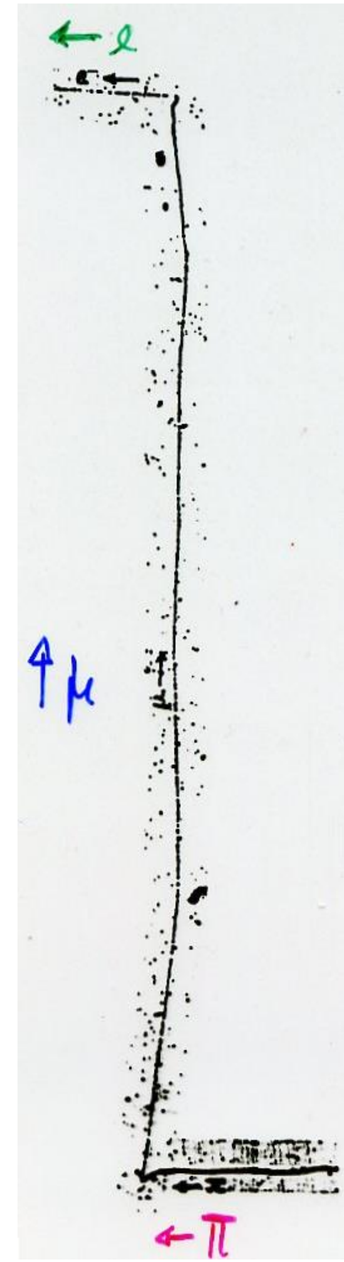


μ (Anderson1937)

Rossi, 1940:

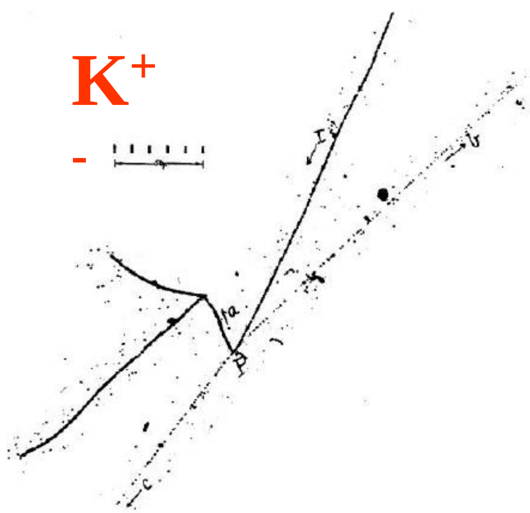
Muon life time.

Time dilation!



π (Latter, Powell1947)

Strong interactions (Yukawa)

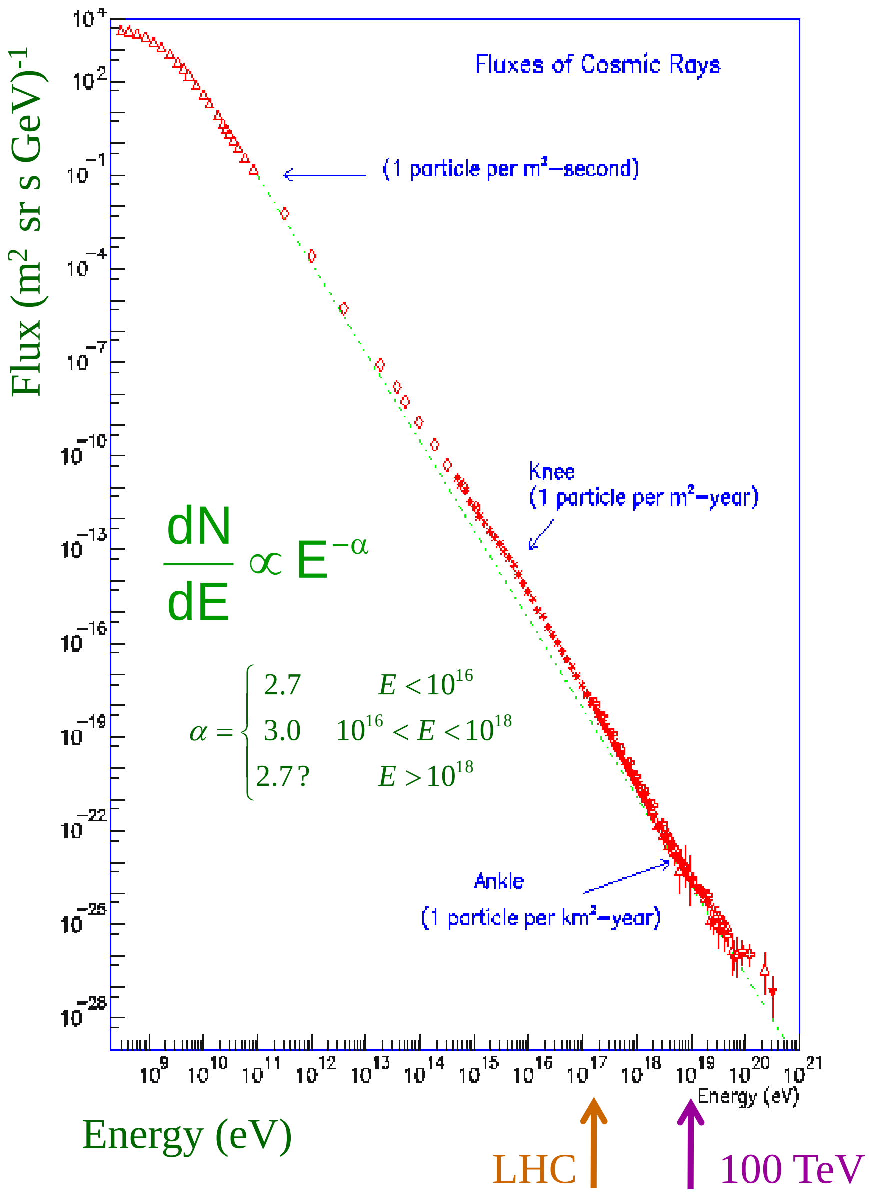


K, Λ, ... (Leprince Ringuet 1944, Rochester , Butter 1947, …)

Strangeness

The present data

Charged cosmic rays (p/nucleus)

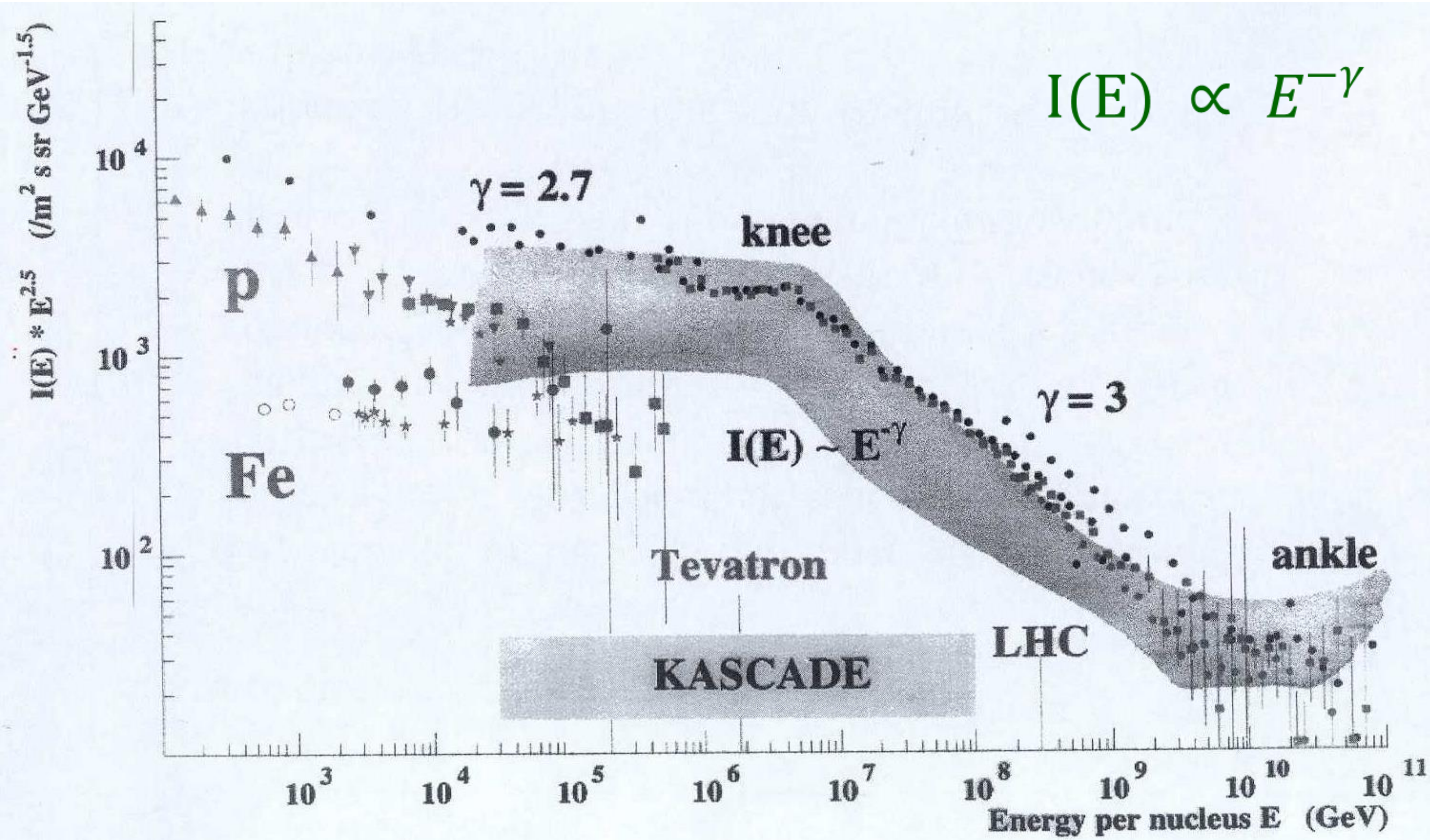


John Linsley, 1962

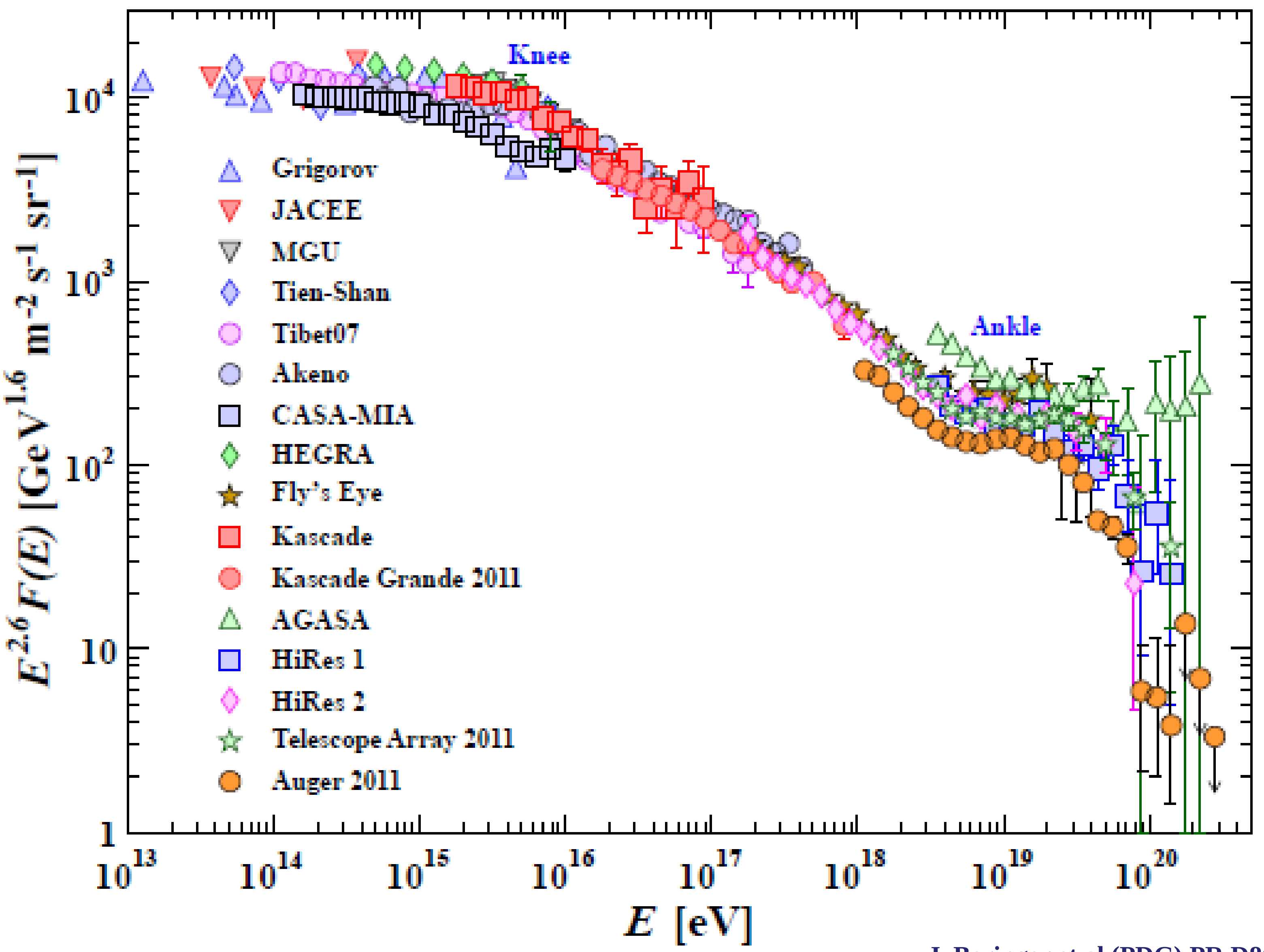
Forward Region
Extreme Energies

Small fluxes
indirect measurements

Anthropomorphic representation

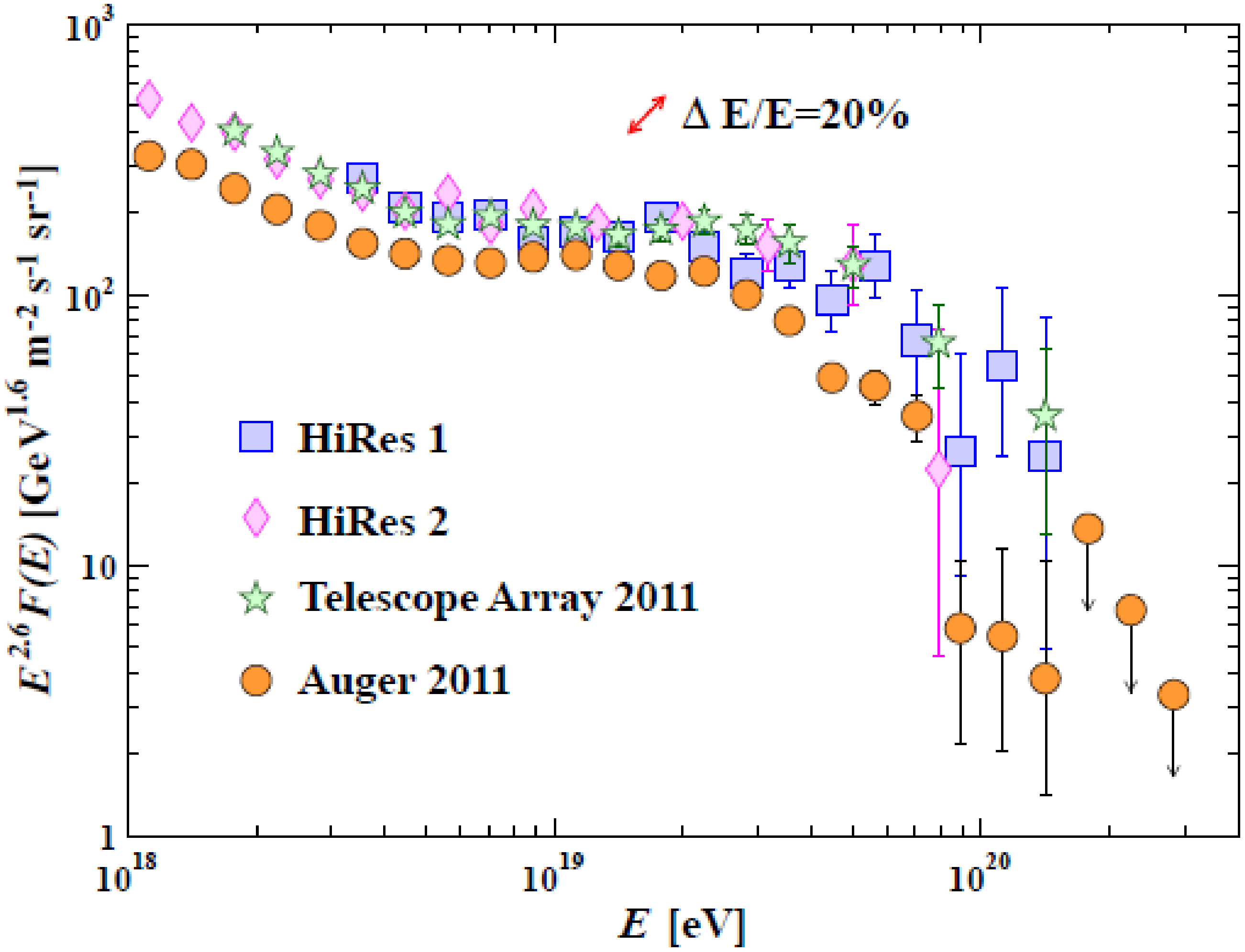


Air shower energy spectrum (E >10^{14} eV)



J. Beringer et al (PDG) PR D86 010001 (2012)

The highest energy region ($E > 10^{18}$ eV)



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Origin (E ~<10^{15} eV)?

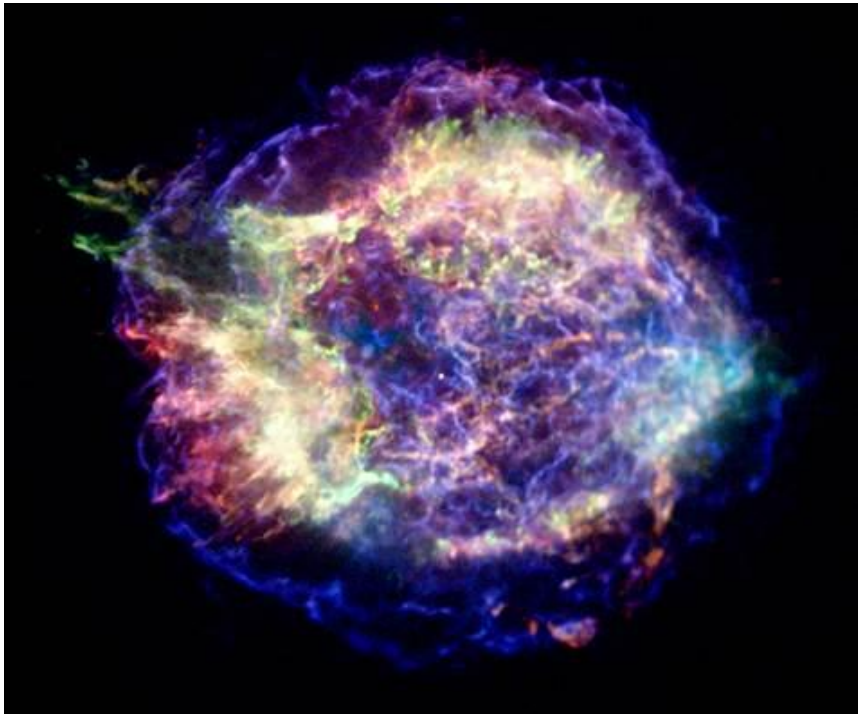
Energy density (cosmic rays)

$$\rho_E \sim \int E \frac{dN}{dE} dE \sim 10^{-12}\ \mathrm{erg/cm^3}$$

$$P \sim \frac{\rho_E V_{galaxy}}{\tau_{esc}} \sim 5.10^{40} erg/s$$

For example, power dissipated by a Supernova (the remnant of a collapsed star)

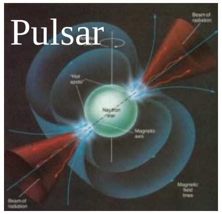
P ~10^{42} erg/s

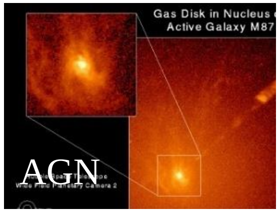


Supernovae in our Galaxy

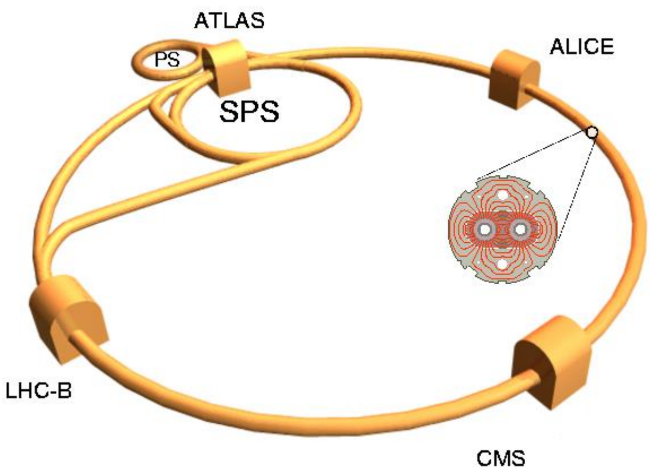
1 SN ~30 Years

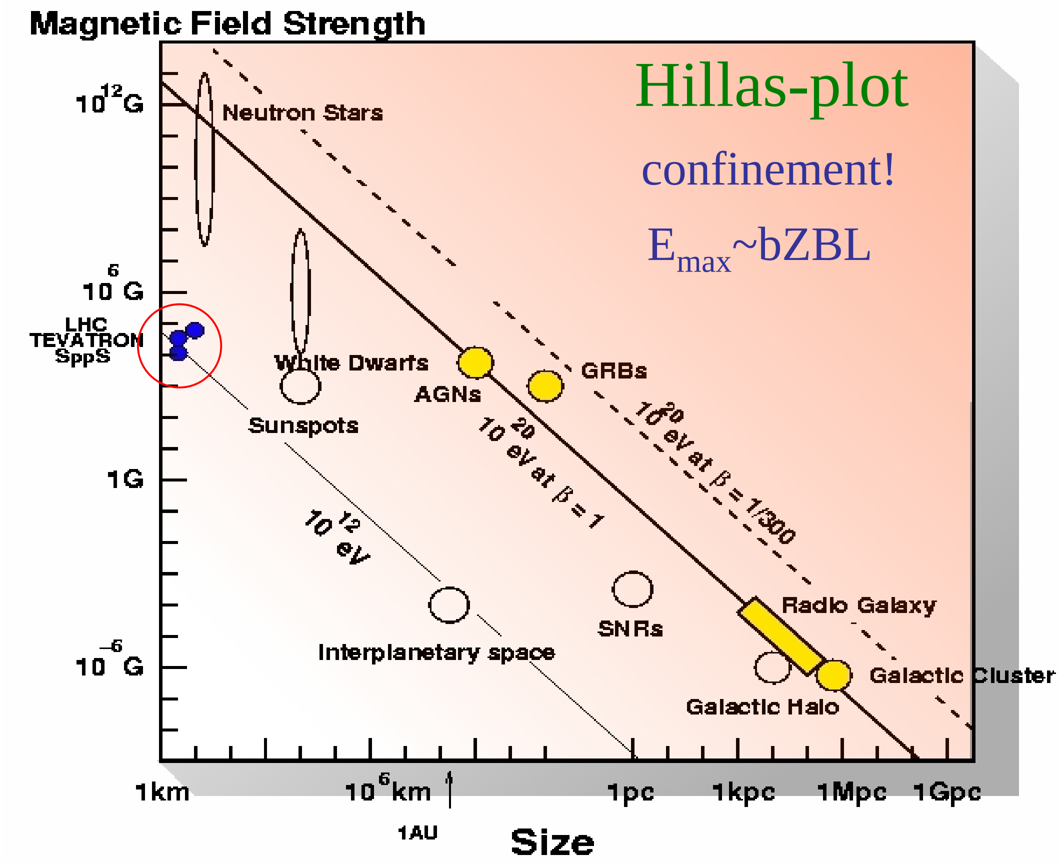
Where can be these accelerators in the Universe?





Large Hadron Collider



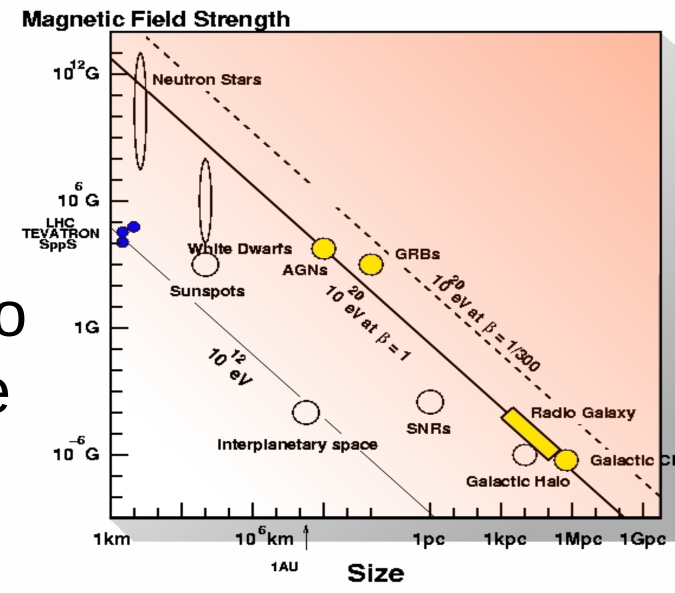


$E \propto BR$

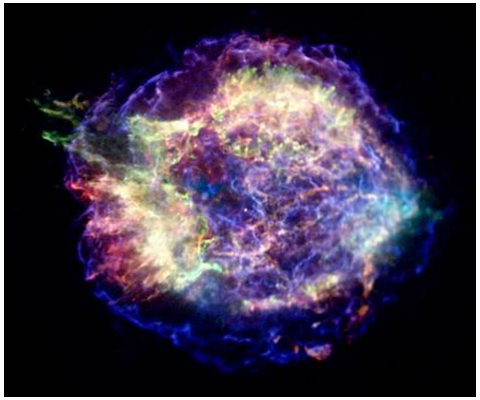
$R \sim 10$ km, $B \sim 10$ T

$E \sim 10$ TeV

A few new terms

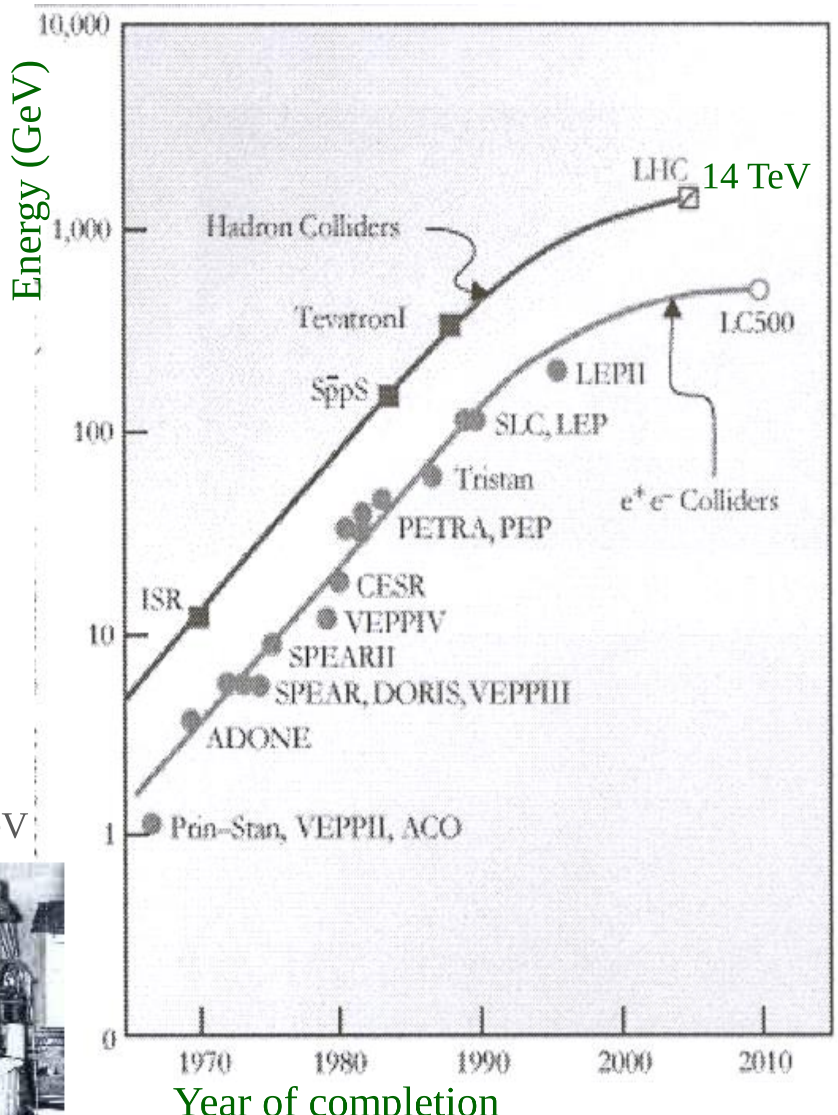


- Stellar endproducts. A star heavier than the Sun collapses at the end of its life into a neutron star (R ~ few km, which can be pulsating – a pulsar) or into a BH, and ejects material in an explosion (SuperNova Remnant).
  - Very large B fields are in the pulsar; magnetic fields also in the SNR



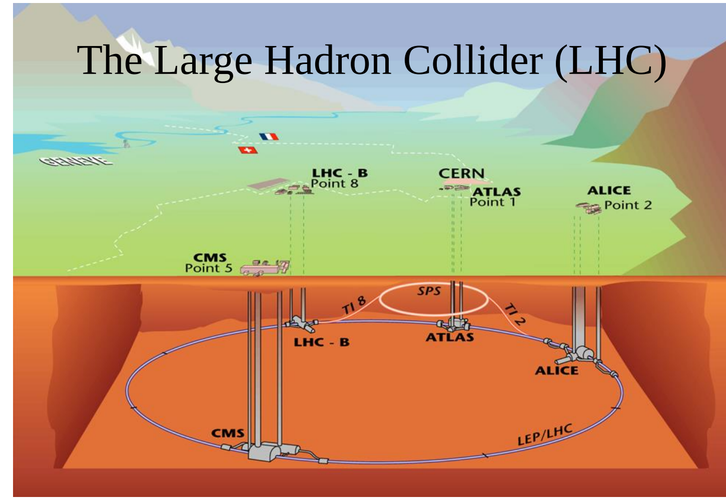
- The centres of galaxies host black holes, often supermassive (millions or even billion solar masses). They might accrete at the expense of the surrounfing matter, and accelerate particles in the process. When they are active, they are called Active Galactic Nuclei.

They surpass human-made accelerators



~ 10 MeV

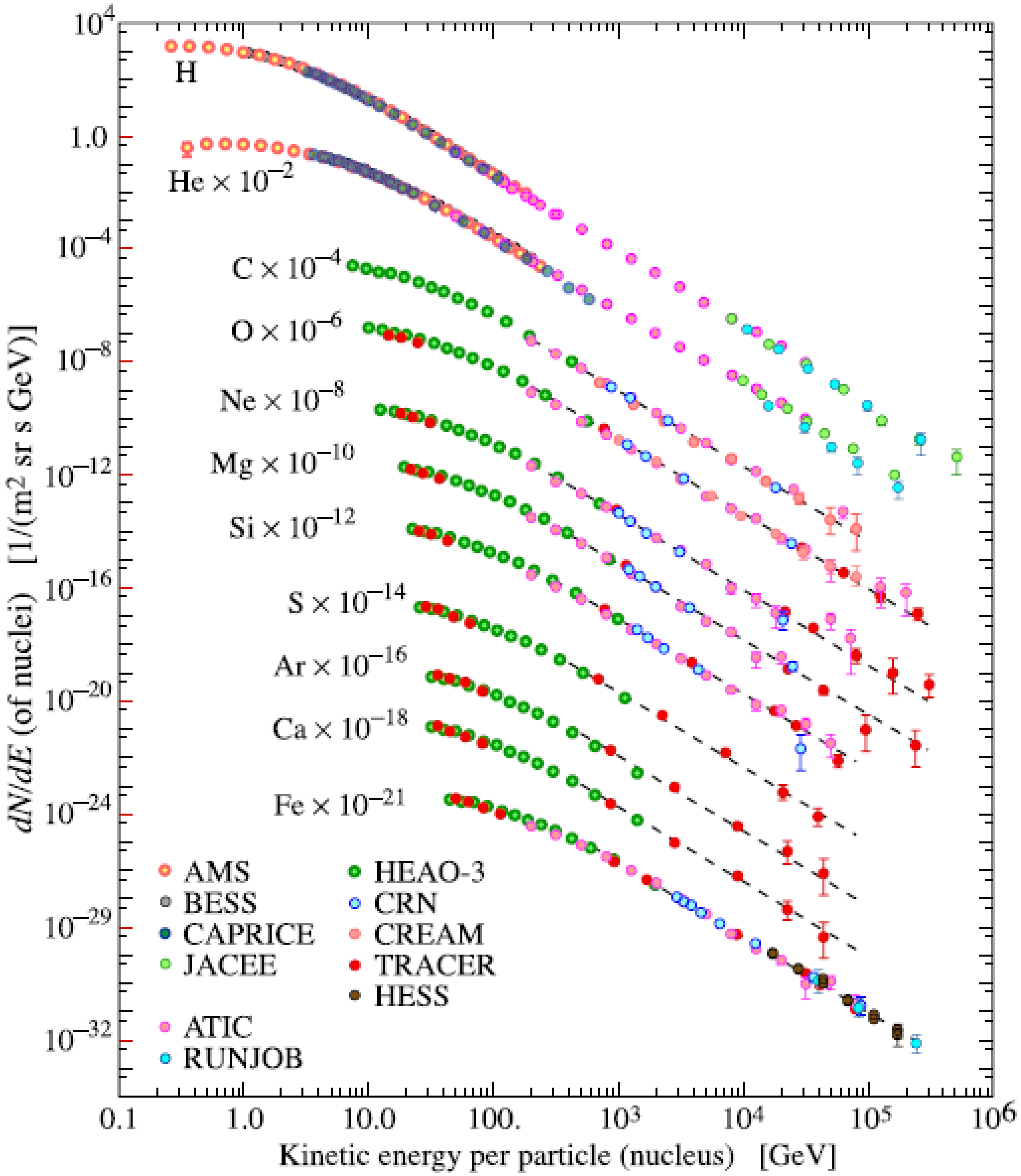
~1930



High Luminosity
Sophisticated detectors

Central region
Energy limited

Energy spectrum ($10^9 < E < 10^{15}$ eV)



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Cosmic-Ray Composition

Z	Element	F	Z	Element	F
1	H	540	13–14	Al-Si	0.19
2	He	26	15–16	P-S	0.03
3–5	Li-B	0.40	17–18	Cl-Ar	0.01
6–8	C-O	2.20	19–20	K-Ca	0.02
9–10	F-Ne	0.30	21–25	Sc-Mn	0.05
11–12	Na-Mg	0.22	26–28	Fe-Ni	0.12

Table 26.1: Relative abundances F of cosmic-ray nuclei at 10.6 GeV/nucleon normalized to oxygen ($\equiv 1$) [6]. The oxygen flux at kinetic energy of 10.6 GeV/nucleon is 3.26×10^{-2} (m^2 s sr GeV/nucleon)$^{-1}$. Abundances of hydrogen and helium are from Refs. [2,3]. Note that one can not use these values to extend the cosmic ray flux to high energy because the power law indicies for each element may differ slightly.

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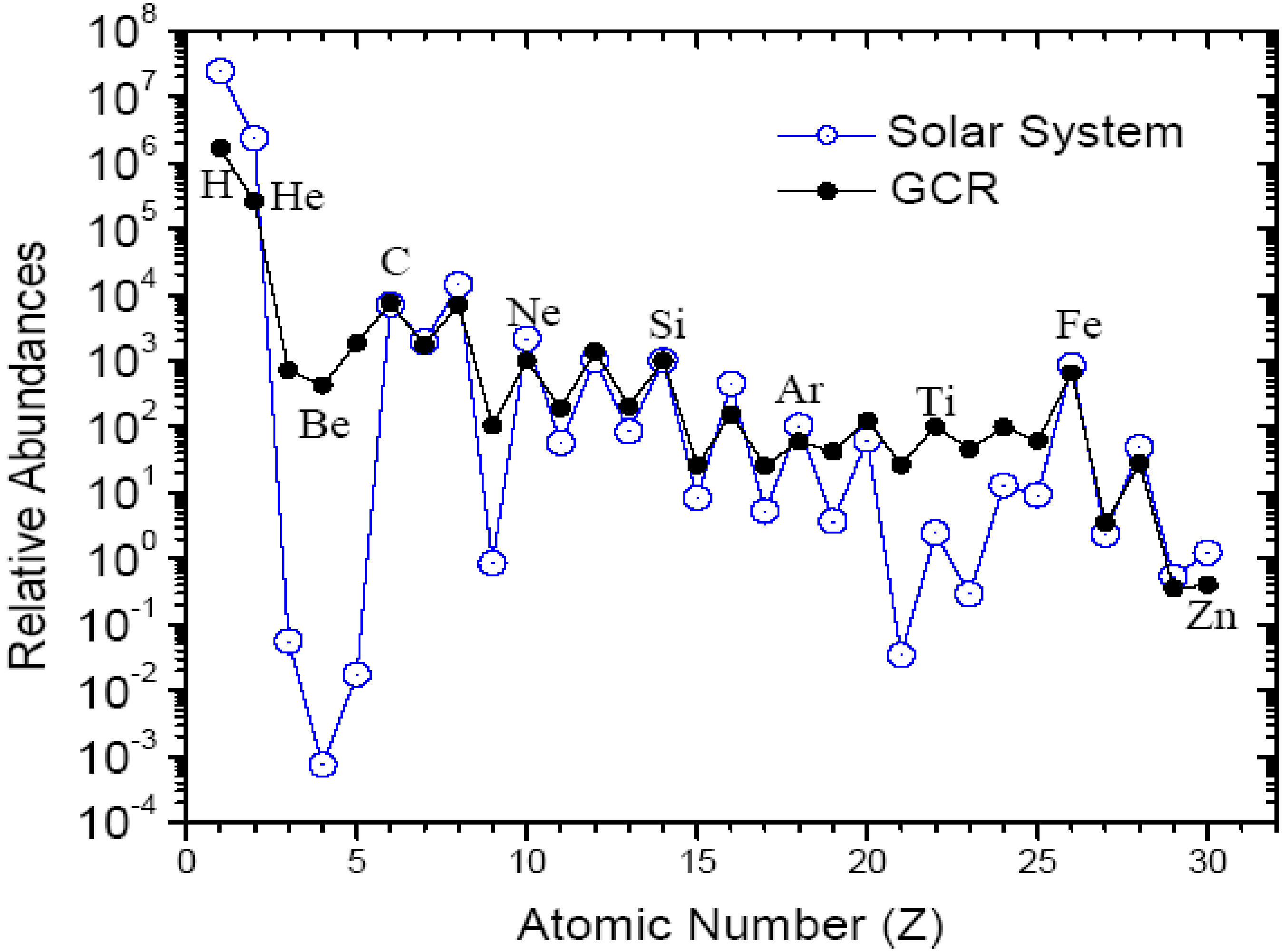
Solar vs Galactic Cosmic Rays



ACE News 83 (2004) - NASA

Electron/positron

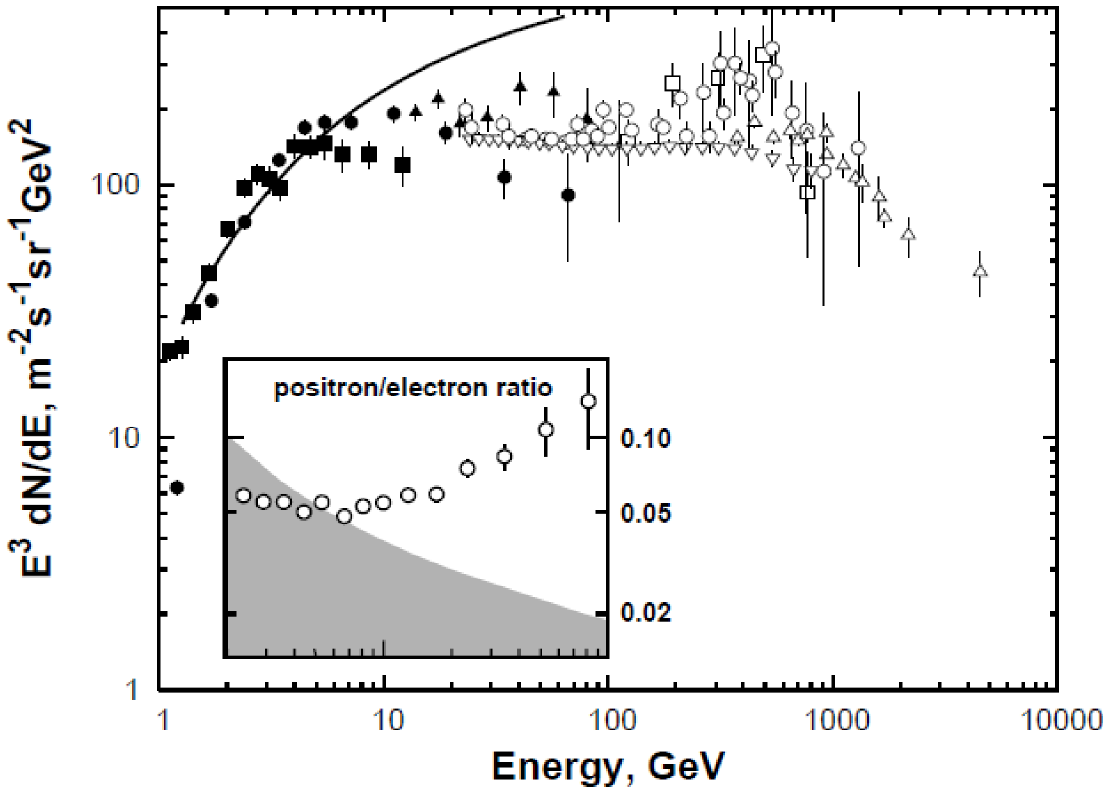


Figure 26.2: Differential spectrum of electrons plus positrons multiplied by E^3 (data from [17–23]) . The line shows the proton spectrum multiplied by 0.01. The inset shows the positron to electron ratio measured by PAMELA [24] compared to the expected decrease [25].

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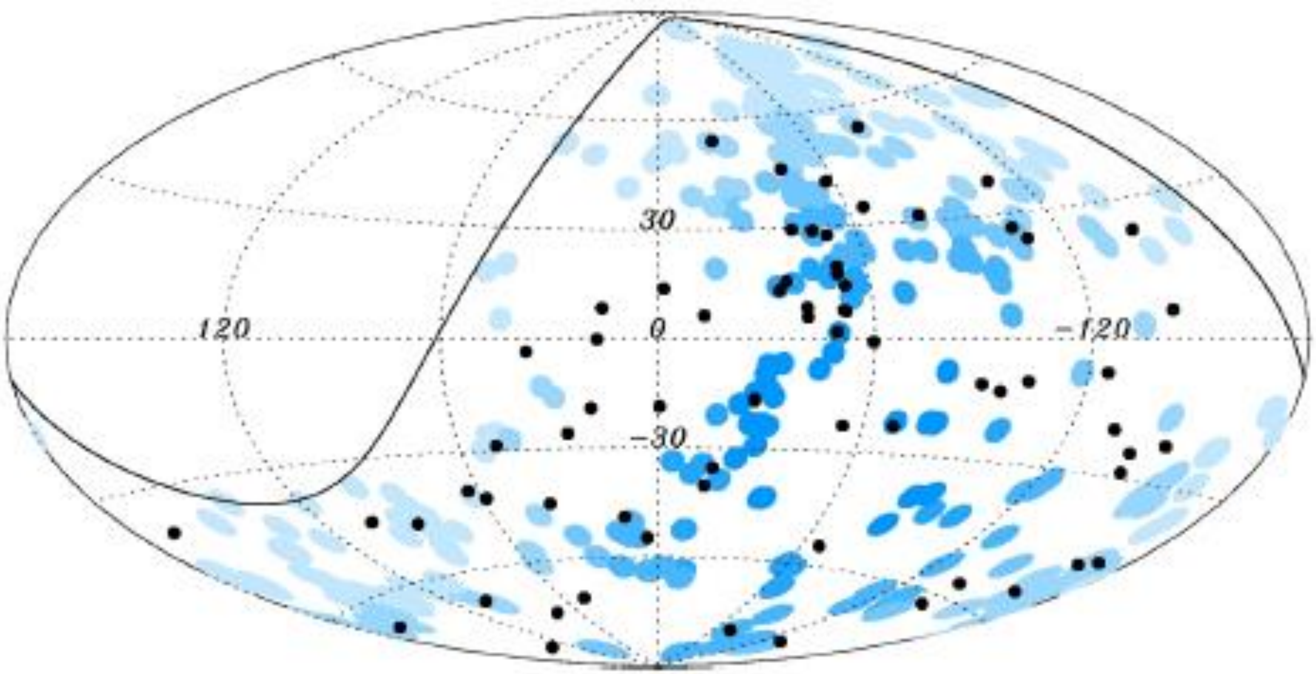
UHECR Correlation with AGNs

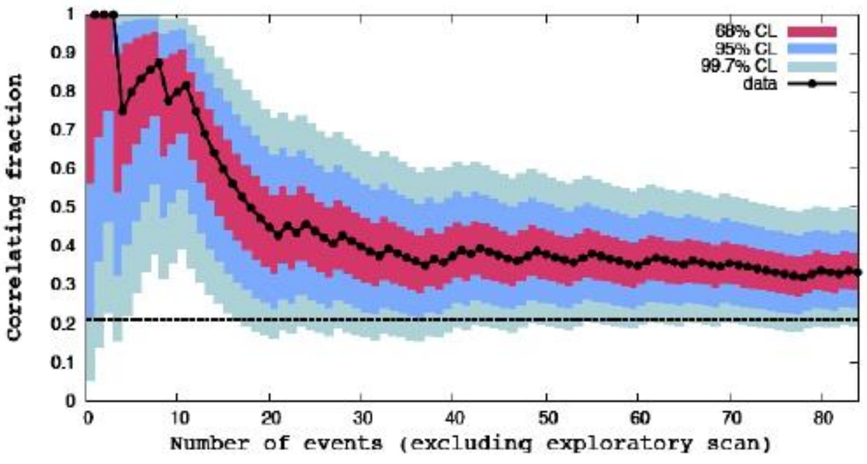


28 out of 84 correlates

Vernon-Cetty-Vernon AGN catalog

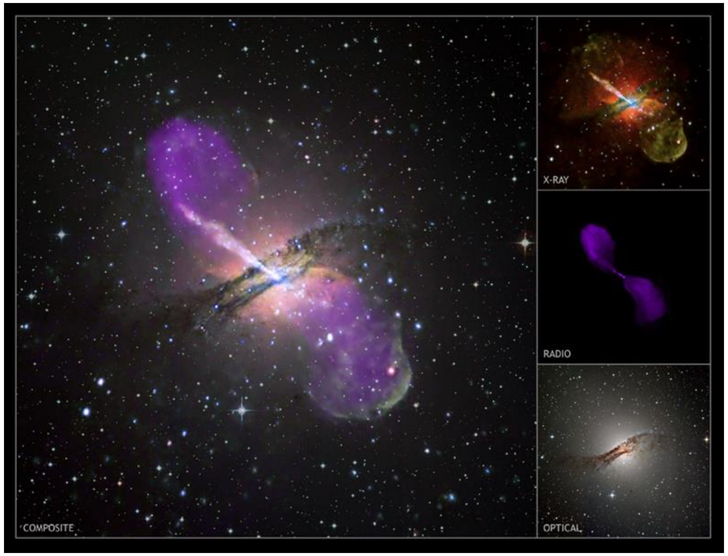
E> 57 EeV, z<0.018, distance < 3.1 deg.

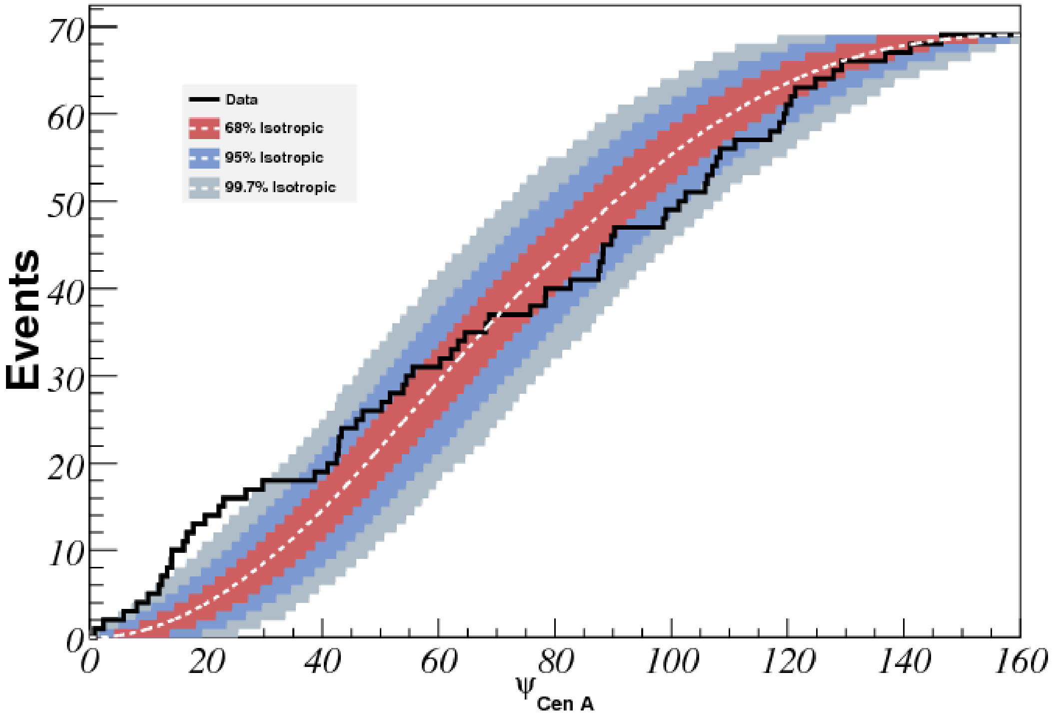
P = 0.006, f = 33 ± 5%



Cen A

Closest (4.6 Mpc) powerful radio galaxy with characteristics jets and lobes, candidate for UHECR acceleration. Auger South.





Cosmic magnetic fields & CR propagation (CR for astronomy?)

$$\frac{r}{1\ \mathrm{pc}} \cong \frac{\frac{E}{1\ \mathrm{PeV}}}{\frac{B}{1\ \mu\mathrm{G}}}$$

- Gyroradius for a proton
  - Typical B field in the Galaxy: ~ 1-3 µG
  - Intergalactic B field largely unknown

    1 nG < B < 1 fG
- If you want to look at the GC (d ~ 8 kpc) you need E > 2 10^{19} eV
  - But only 1 particle / km2 / year
  - And: no galactic emitters expected at this energy
- But in principle one could look outside the galaxy, were B is smaller and there are SMBHs…

extremely difficult

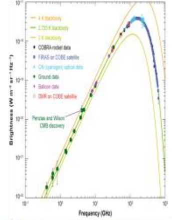
=> Locating the sources of charged CR is ~~impossible~~ AT GROUND

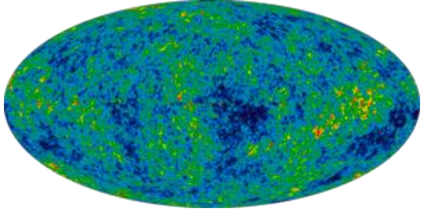
- We need to detect a large statistics of protons with E between 10^{19} eV and 10^{21} eV
- Areas ~ 30 thousand km^2 (1/10 of Italy), ~impossible to find
- Needs satellites
- VHE photons
- Neutrinos
  - Detected only from Sun and SN1987A
- Gravitons
  - Undetected up to now; we shall not discuss them

Thermal radiation: Black Body Spectrum

Cosmic Microwave Background:

2.7 K





A Galactic gas cloud

called Rho Ophiuchi:

60 K

Dim star near the

center of the Orion Nebula:

600 K

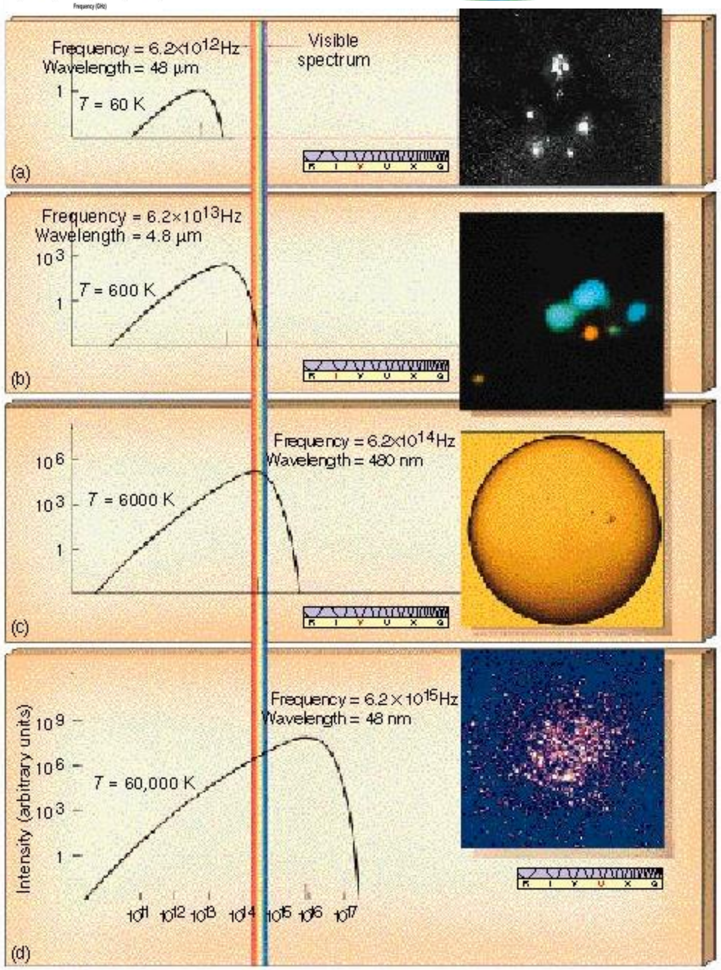
the Sun:

6000 K

Cluster of very bright stars, Omega Centauri,

as observed from the space:

60,000 K

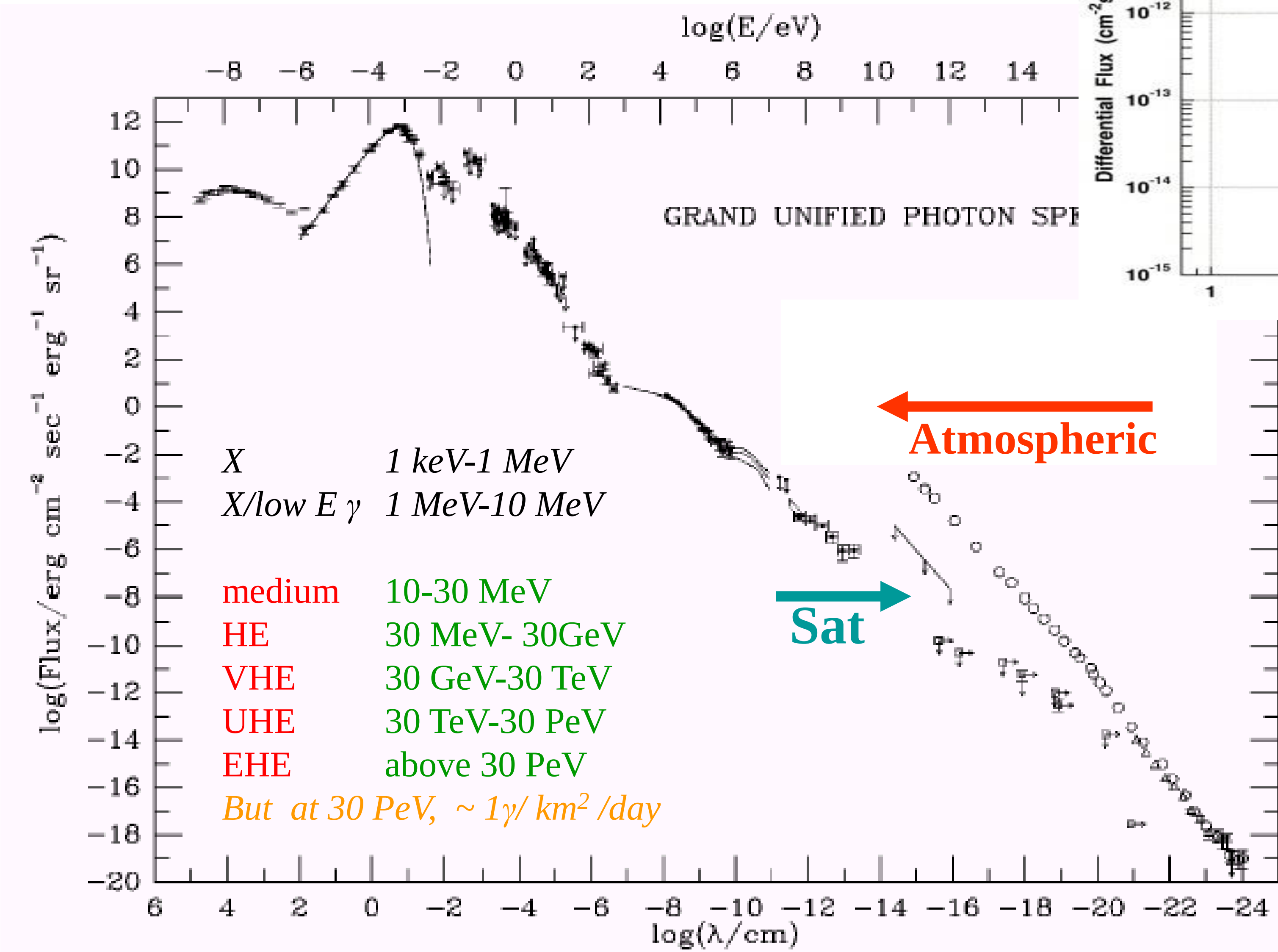


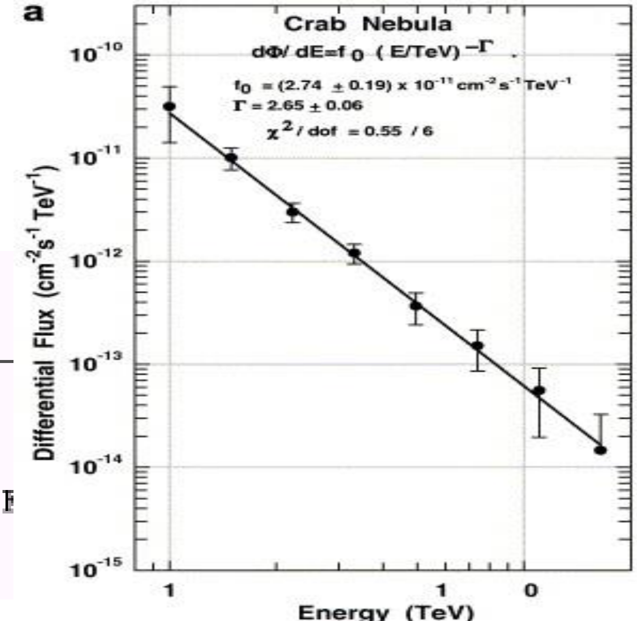
Accretion Disks can reach

temperatures >> 10^5 K

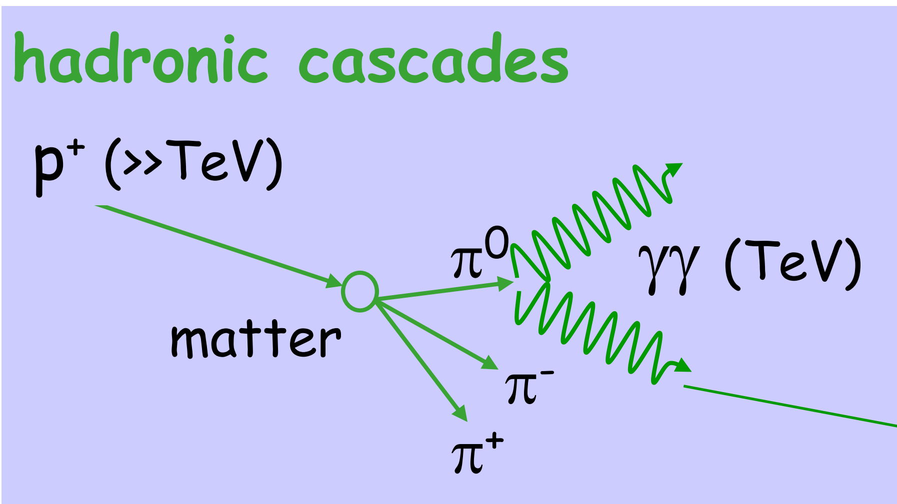
But this is still ~1 keV, in the X-Ray band!

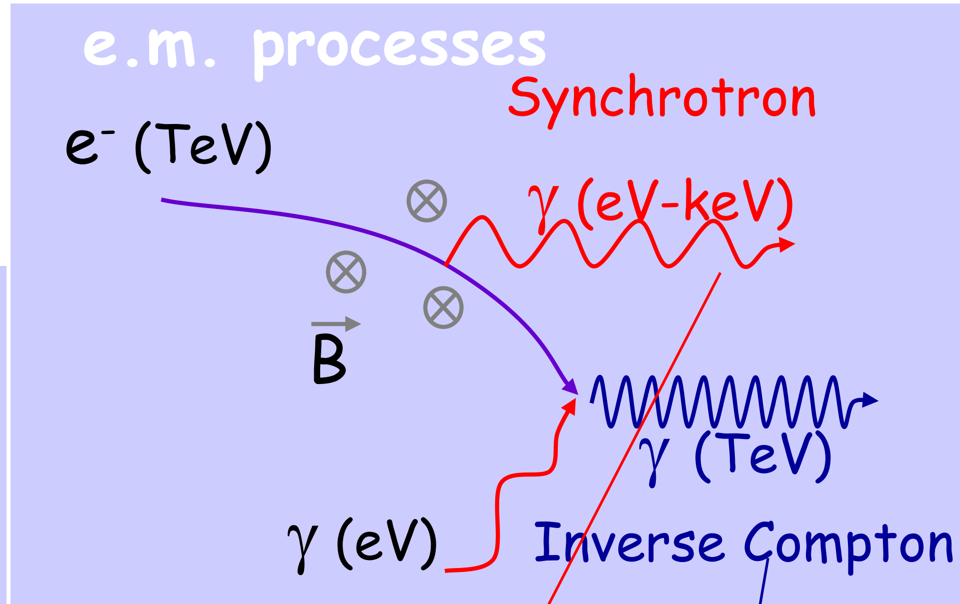
γ energy spectrum

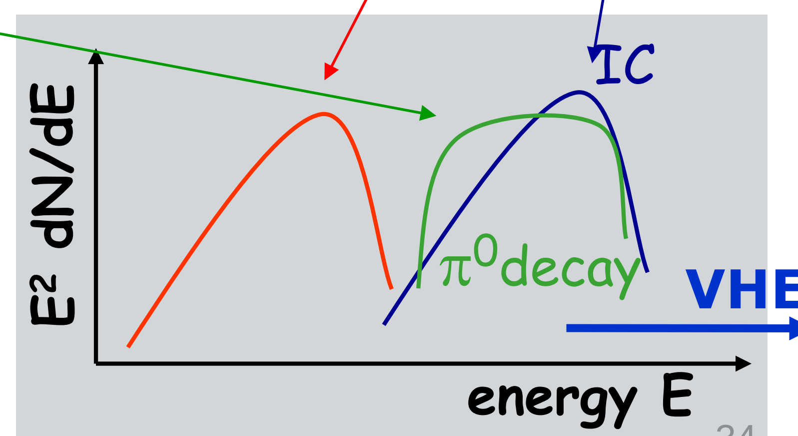




Cosmic γ rays: two different production mechanisms expected to be at work







In the VHE region,

$dN/dE \sim E^{-\Gamma}$ (Γ: spectral index)

To distinguish between had/leptonic origin

study Spectral Energy Distribution (SED):

(differential flux) $\cdot E^2$

Leptonic vs. Hadronic models for γ emission

- SSC: currently explain most emissions
  - easy to accelerate electrons to TeV energies
  - easy to produce synchrotron and IC gamma-rays

  But:
  - recent results would require more sophisticated leptonic models

- Hadronic Models:
  - protons interacting with ambient hadronic targets -> neutrinos (1)
    - But needs adequate targets: works well for SNR, more difficult for AGN
  - protons interacting with photons (hadronic photoproduction) -> neutrinos (2)
  - proton synchrotron (no neutrinos)
    - very large magnetic fields

High Energy γ rays: non-thermal Universe

- Particles accelerated in extreme environments interact with medium
  - Gas and dust; Radiation fields – Radio, IR, Optical, …; Intergalactic Magnetic Fields, …
- Gamma rays traveling to us!
  - HE: 30 MeV to 30 GeV
  - VHE: 30 GeV to 30 TeV

Plus: “new” particles (e.g. Dark Matter)

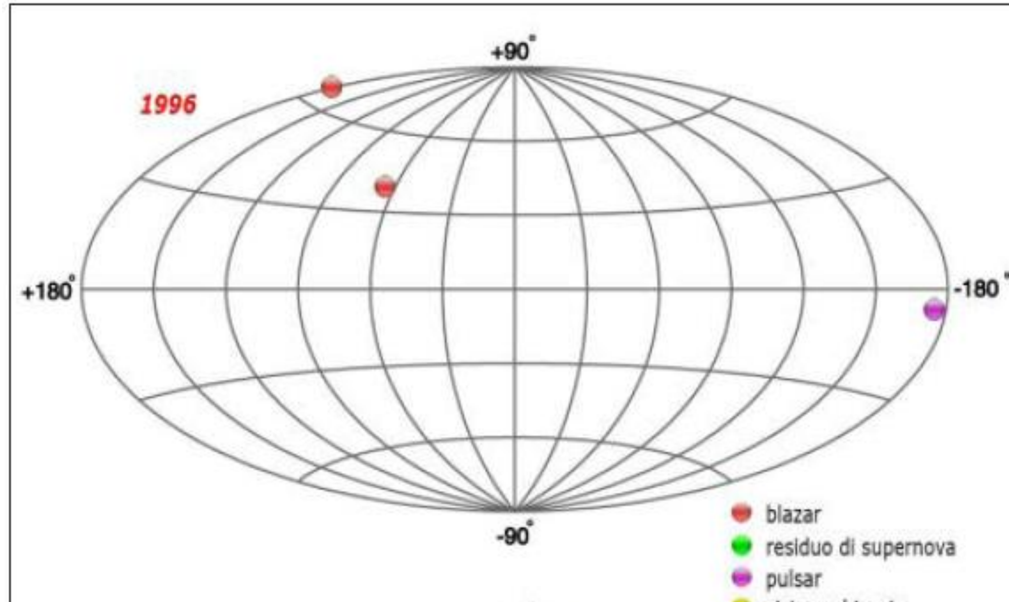
- No deflection from magnetic fields, gammas point ~ to the sources

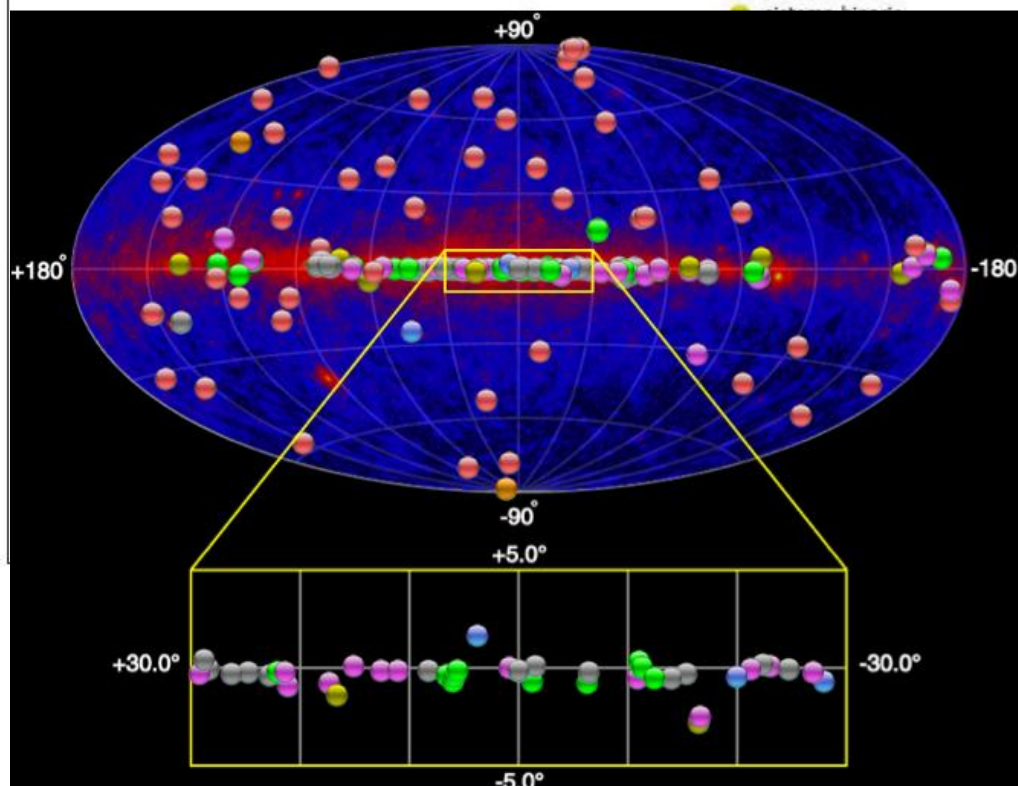
  Gamma rays can trace cosmic rays at energies ~10x
- Large mean free path
  - Regions otherwise opaque can be transparent to X/γ

Studying Gamma Rays allows us to see these aspects of the Universe

VHE sources have been located using gammas

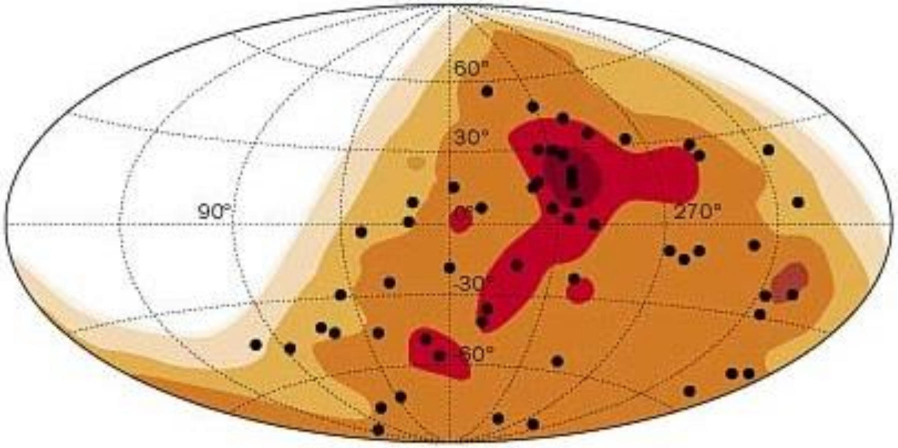
- Thanks mostly to Cherenkov telescopes, imaging of VHE (> 30 GeV) galactic sources and discovery of many new galactic and extragalactic sources: ~ 150 (and >200 papers) in the last 7 years
  - And also a better knowledge of the diffuse gammas and electrons
- A comparable success in HE (the Fermi realm); a 10x increase in the number of sources
- A new tool for cosmic-ray physics and fundamental physics
- *In the Galaxy, mostly associated to stellar endproducts (PWN in particular). Extragalactic emission associated to AGN*

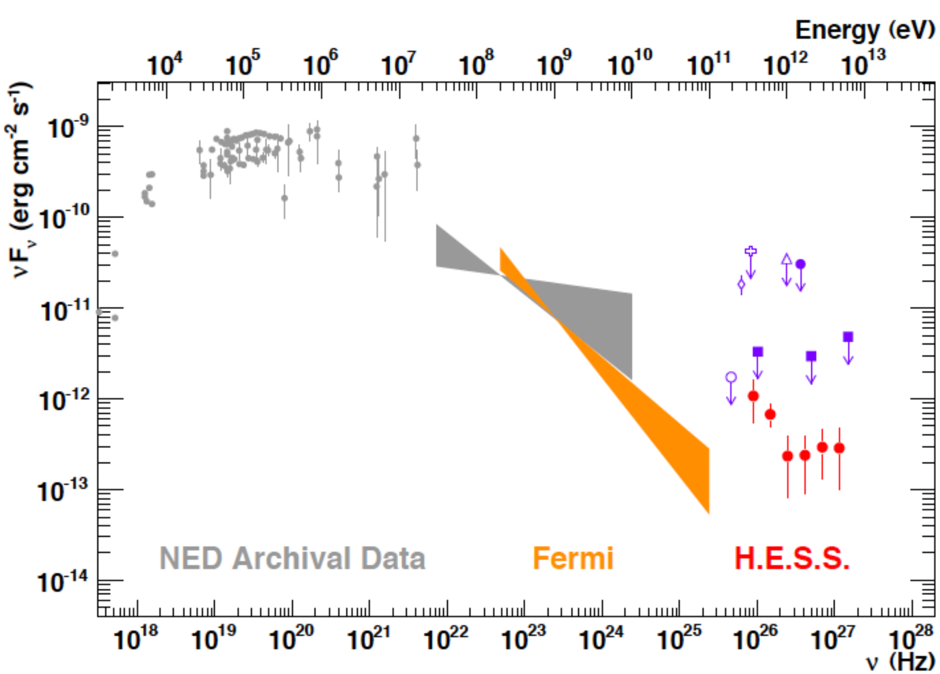


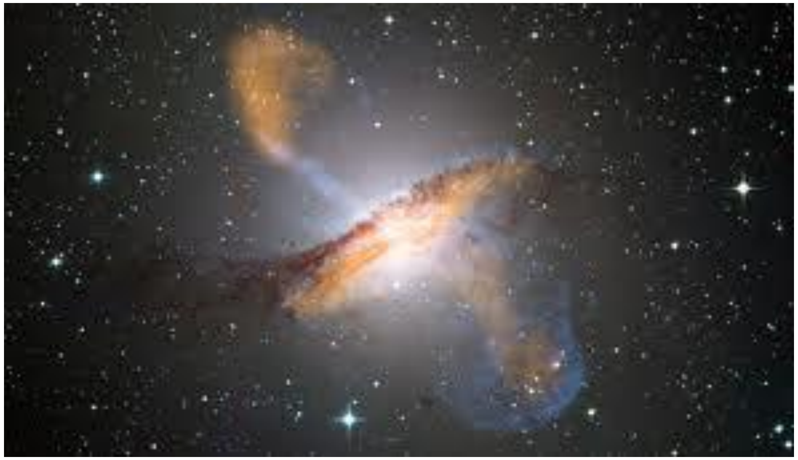


Cen A

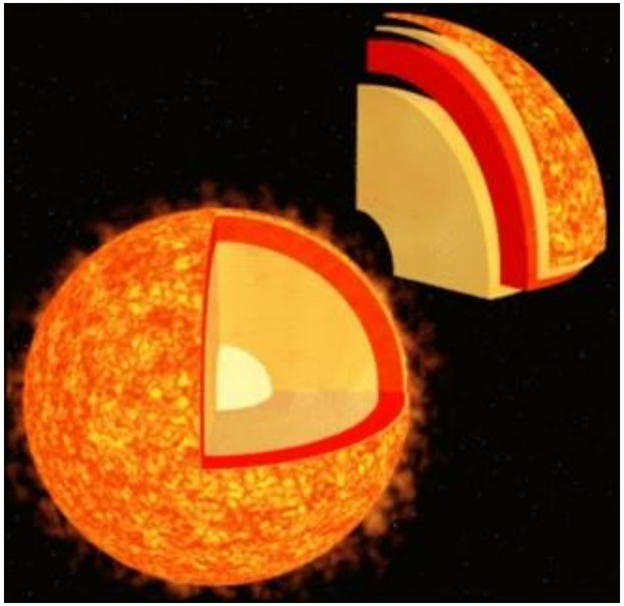
- Located at a distance of ~13 Mly, the best candidate as a CR emitter from Auger
- Very faint VHE gamma-ray emitter (HESS 2009)

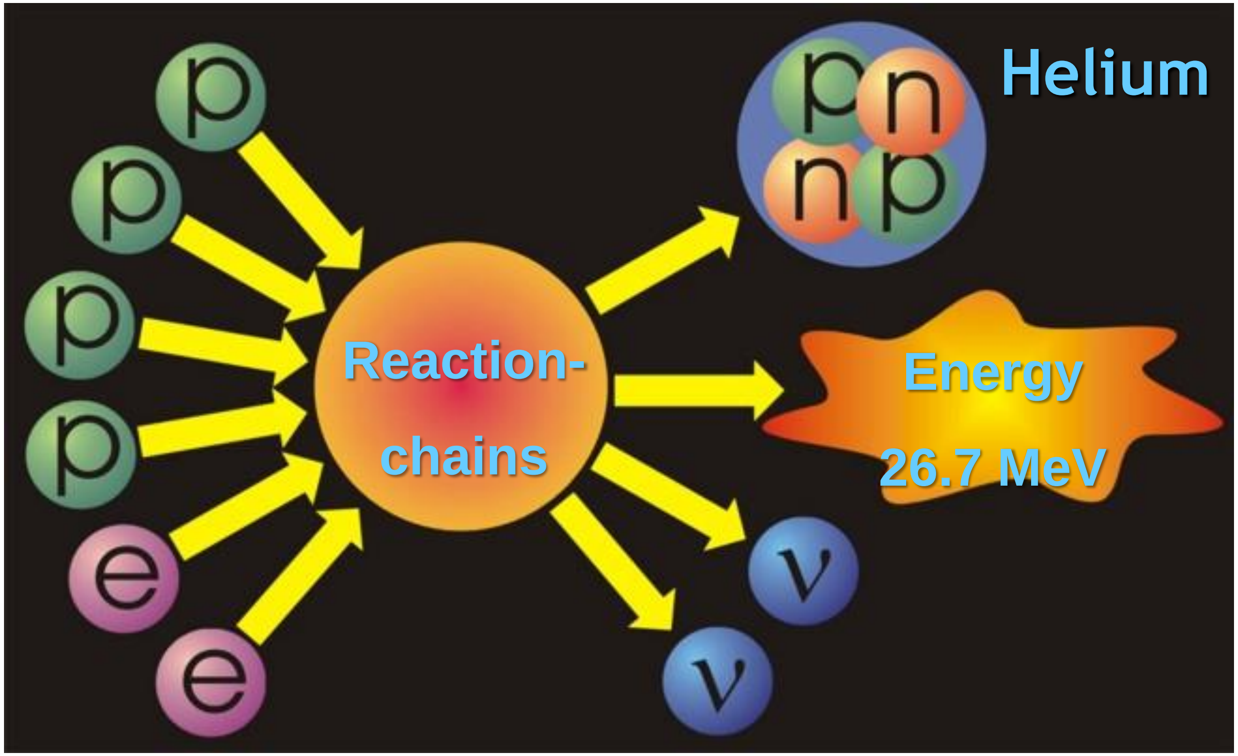






Neutrinos





Solar radiation: 98 % light

2 % neutrinos

At Earth 66 billion neutrinos/cm^2 s

Hans Bethe (1906–2005, Nobel prize 1967)

Thermonuclear reaction chains (1938)

Neutrinos

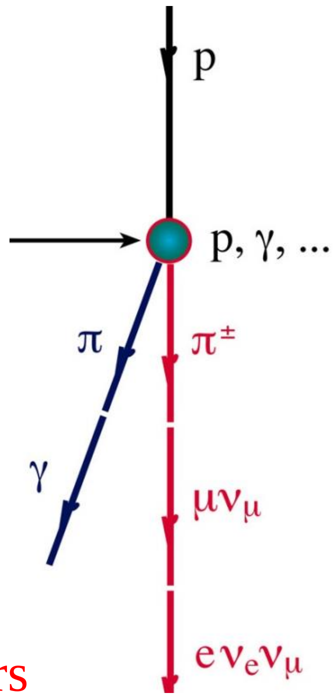
- Neutrinos play a very special role in particle astrophysics. Their cross section is small, and they can leave production sites without interacting => can carry information about conditions deep in the core of astrophysical objects that produce them
- They are produced in the nuclear reaction chains by which stars generate energy. Each conversion of 4p into He produces two neutrinos - the Sun emits ~2×10^{38} neutrinos per second
- They are also produced in nature's most violent explosions, including the Big Bang
- They are produced as secondary byproducts of cosmic-ray collisions also in the atmosphere. Detection of these neutrinos can help constraining properties of the primary cosmic ray spectrum, more effectively than photons. Neutrinos produced by reactions of ultra-high-energy cosmic rays can provide information on otherwise inaccessible cosmic accelerators

CR: clear synergy gammas-neutrinos

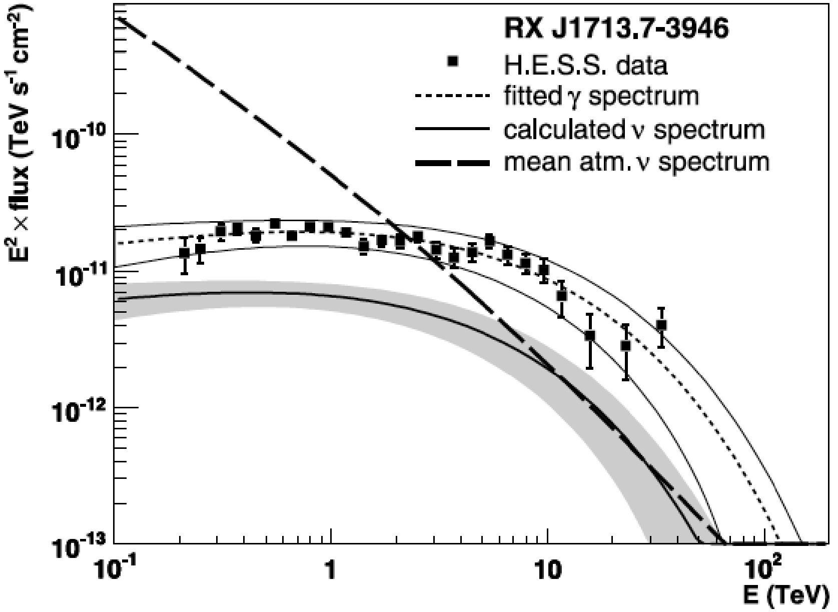
- Smoking gun would be a correlation of VHE CR (difficult: magnetic fields) or a neutrino signal
- Many model uncertainties present in the gamma/p relation disappear when studying gamma/neutrino

$$\frac{dN_\nu}{dE} \approx \frac{1}{2}\frac{dN_\gamma}{dE}$$

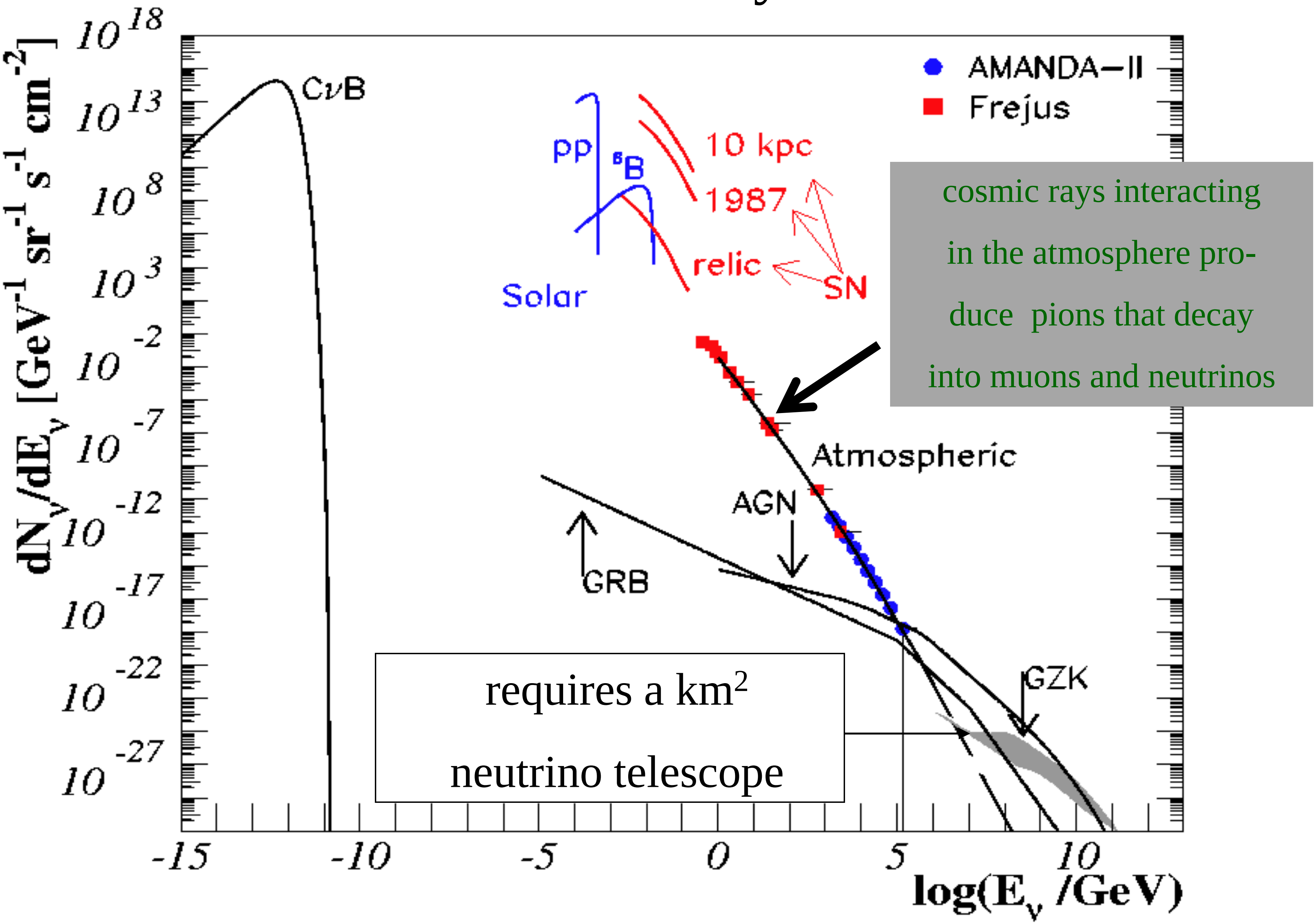
(reflects the fact that pions decay into gamma rays and neutrinos that carry 1/2 and 1/4 of the energy of the parent. This assumes that the four leptons in the charged pion decay equally share the charged pion's energy)



⇒Very accurate input for neutrino detectors

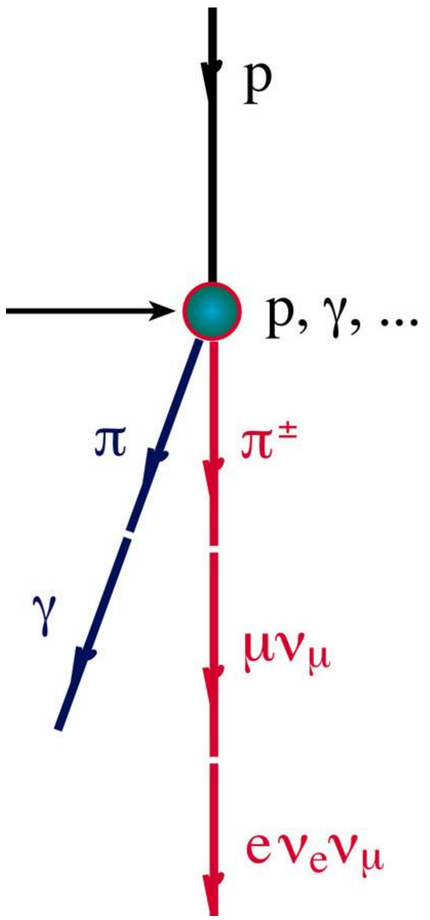


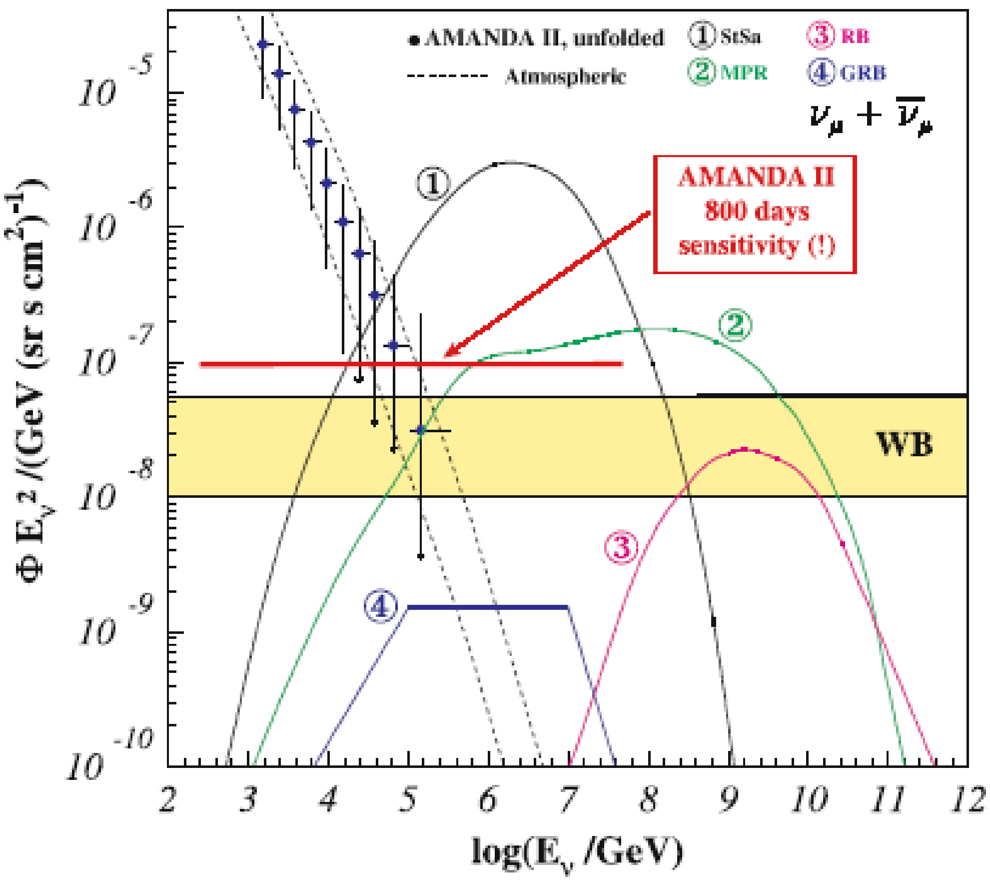
neutrino sky



ν energy spectrum

secondary
γ and ν beams!



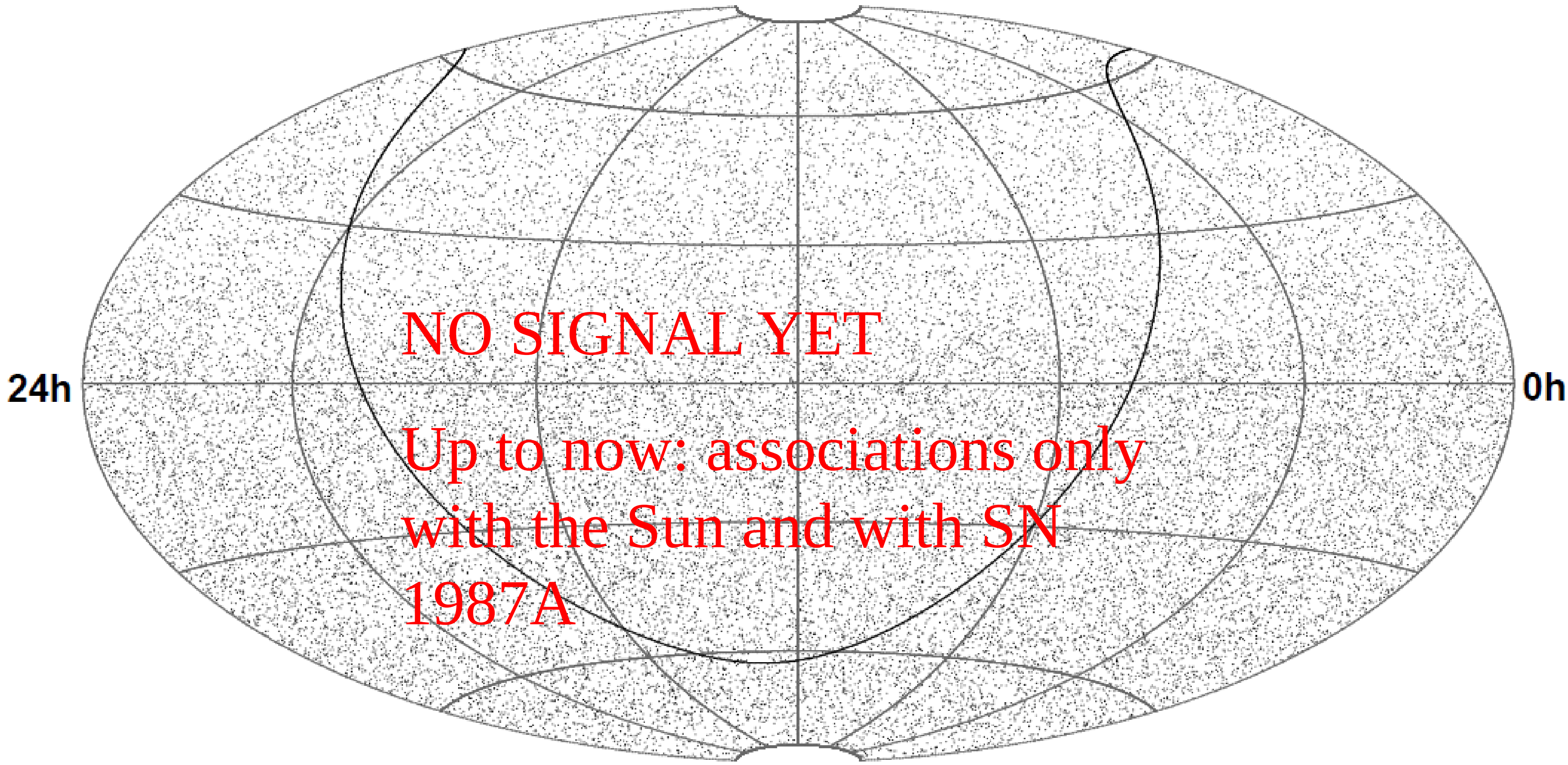


BUT no measurements above
E > 10^6 GeV !

IceCube 40 strings

operated 375.5 days

northern sky: 14139 neutrinos

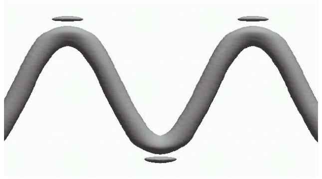


southern sky: 23151 muons

search for

- clustering
- high energy (>> 100 TeV)

? beams



New neutral particles ?

Neutralino, axion, glueballino, enhanced neutrino-nucleon cross-section ...

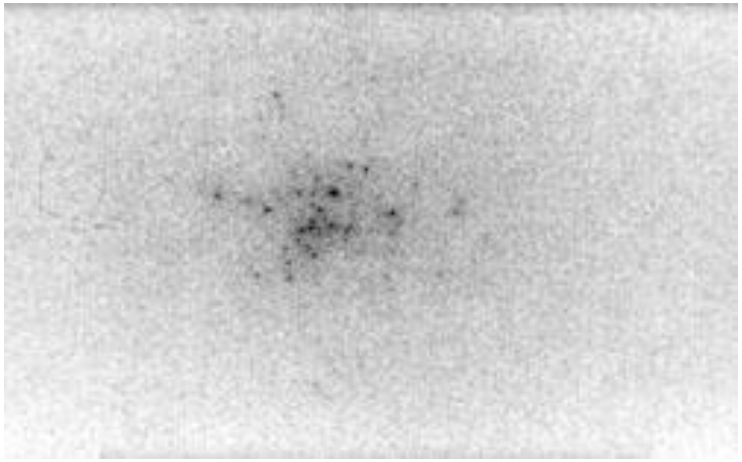
Decay products of super-heavy X particles ~ GUT scale

Gauge bosons, Higgs bosons, super-heavy fermions ...

cosmic strings, magnetic monopoles...

Several "anomalous" events

- Almost no photons
- highly penetrating hadrons



Are they real ??

The sources

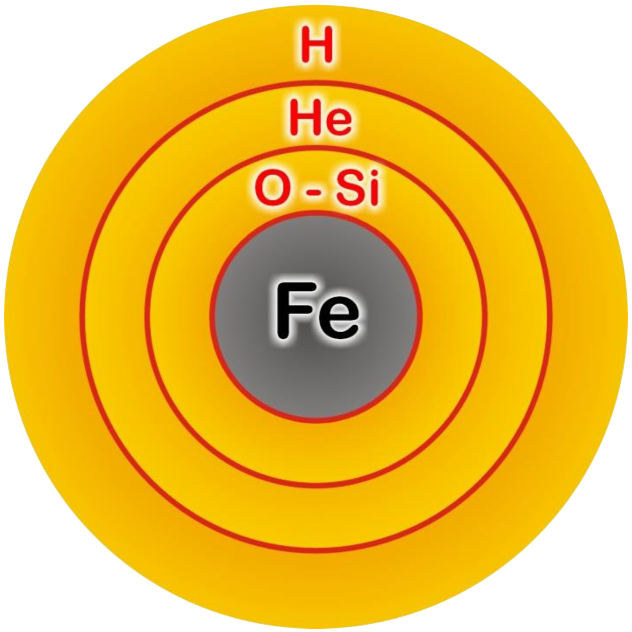
Where to find these accelerators in the Universe?

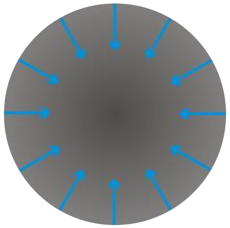
- Stellar endproducts
- AGN

(one has energy from the gravitational potential energy, and magnetic fields from plasma motions)

Stellar endproducts (supernova remnants)

A massive star begins its lifetime burning the H in its core under conditions of equilibrium. When the H is exhausted, the core contracts until 3α -> 12C can take place. He is then burned to exhaustion. This pattern (fuel exhaustion, contraction, heating, and ignition of the ashes of the previous cycle) might repeat several times depending on the mass, leading finally to an explosion. A 25-solar-mass star would go through the set of burning cycles ending up in the burning of Si to Fe in about 7 My, with the final explosion taking ~days





Evolution of Stars depends on mass

$M < 0.08\, M_{sun}$	Never ignites hydrogen → cools ("hydrogen white dwarf")	Brown dwarf
$0.08 < M \lesssim 0.8\, M_{sun}$	Hydrogen burning not completed in Hubble time	Low-mass main-squence star
$0.8 \lesssim M \lesssim 2\, M_{sun}$	Degenerate helium core after hydrogen exhaustion	• Carbon-oxygen white dwarf • Planetary nebula
$2 \lesssim M \lesssim 5\text{–}8\, M_{sun}$	Helium ignition non-degenerate	
$8\, M_{sun} \lesssim M < ???$	All burning cycles → Onion skin structure with degenerate iron core Core collapse supernova	• Neutron star (often pulsar) • Sometimes black hole? • Supernova remnant (SNR), e.g. crab nebula

Rate of SN in our galaxy: ~ 1 every 30 years (CR considerations); ~1/century (astrophysical cons.)

Observed: ~1/400 years

SNR (continued)

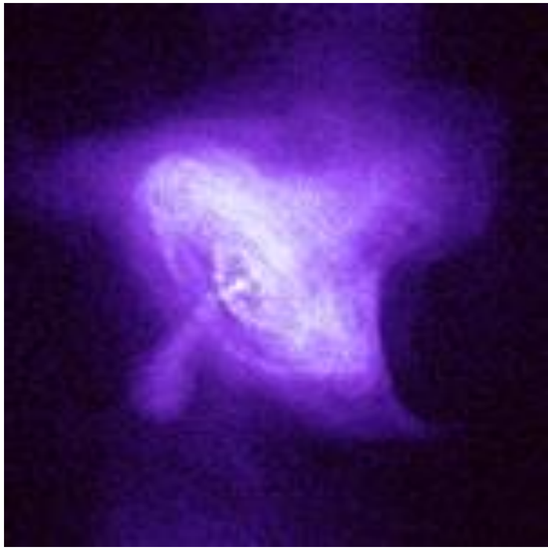
- If mass is large enough to explode/collapse, the supernova remnant (SNR) is the structure left over after a supernova explosion: a high density n star (or a BH) lies at the center of the exploded star, whereas the ejecta appear as an expanding bubble of hot gas that shocks and sweeps up the interstellar medium.

SNR (continued)

- Typical velocities for the expulsion of the material are of the order of c/100
- The shock slows down over time as it sweeps up the ambient medium, but it can expand over tens of thousands of years and over tens of pc before its speed falls below the local sound speed
  - Typical duration depends on the mass, and can go between 10ky and 100 ky
- Based on their emission and morphology (which are actually related, and related to age and mass), SNRs are generally classified under three categories: shell-type, pulsar-wind nebulae (PWN), and composite

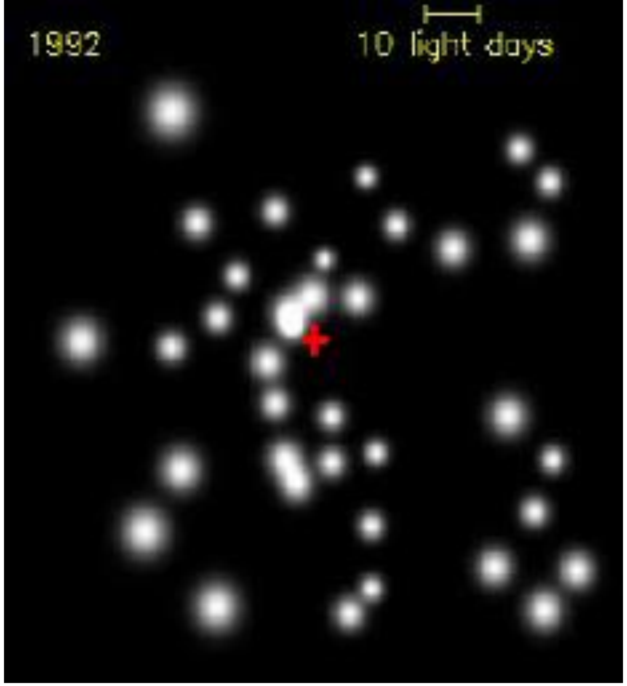
SNR (continued)

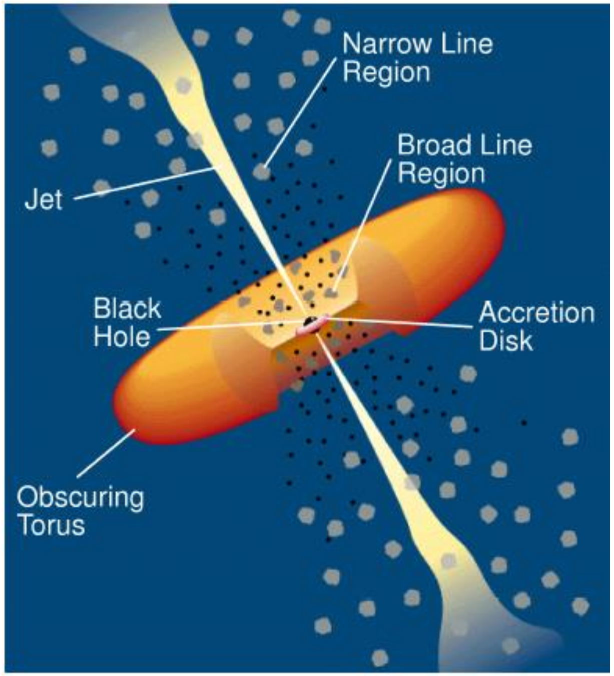
- Shell supernova remnants. As the shockwave from the supernova explosion plows through space, it heats and stirs up any interstellar material it encounters, which produces a big shell of hot material in space. Magnetic fields strengths are estimated to be from 10 μG to 1 mG.
- Pulsar-wind nebulae (PWN) are SNR where a young pulsar is slowing down in rotation: the rate of decrease of rotational energy is in the range 10^{32} to 10^{39} erg/s. A small part of this energy goes into the pulsed electromagnetic radiation observed from the pulsar, most of it goes into an outflowing relativistic magnetized particle wind: due to external pressure, this wind abruptly decelerates at a termination shock, beyond which the pulsar wind radiates synchrotron emission - so resulting in a PWN. The best know case is the Crab Nebula.
- Composite are the SNR that cannot be classified in any of the above



AGN

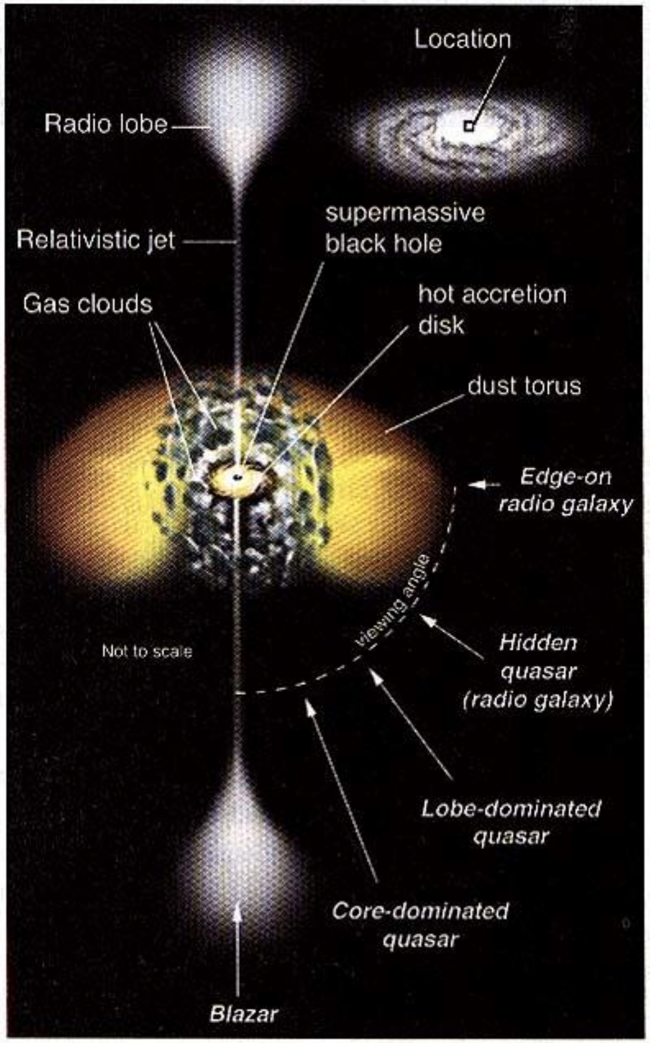
- Supermassive black holes (SMBH) of 1M-10G solar masses reside in the cores of most galaxies (the centre of our Galaxy hosts a BH ~4 million solar masses, its mass having been determined by the orbital motion of nearly stars.
- Their fueling by infalling matter can produce a spectacular activity; when they are active, i.e., they are powered by accretion at the expenses of nearby matter, these BH are called Active Galactic Nuclei (AGN).





AGN

- It is believed that a "unified model" accounts for all AGN . The SMBH and its inner accretion disk is surrounded by a dusty torus of matter, and the type of active galaxy that is seen depends on the orientation of the torus and jets relative to the observer's line of sight.
- The jet radiates strongly along its axis, also due to the Lorentz boost. The view of an observer, who is looking very close to this axis, will be dominated by the jet emission, and a possibly variable source with no spectral lines will be seen: this is called a BL Lac object, or blazar
- Looking at a modest angle to the jet, an observer will see an unobscured compact source inside the torus; this is in general called a quasar
- From a viewpoint closer to the plane of the torus, the central engine is hidden, and one observes the jets and lobes (extended radio-emitting clouds) of a radio galaxy
- Typical values of B are of the order of 10 G to 10000 G.
- The jet can be traced down to a scale size of order 0.01 pc which is < 100 000 times its total length and <100 times the radius of the BH

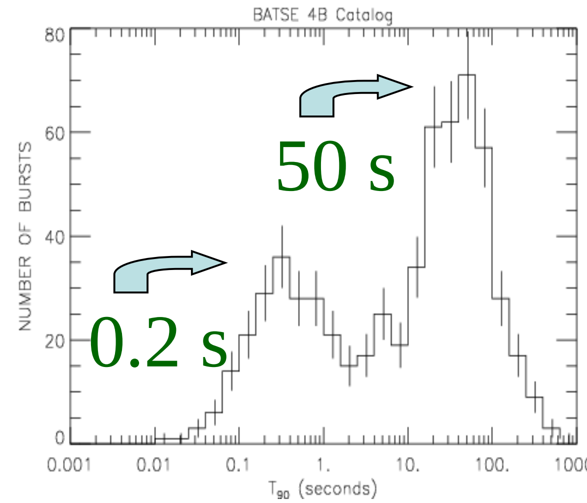


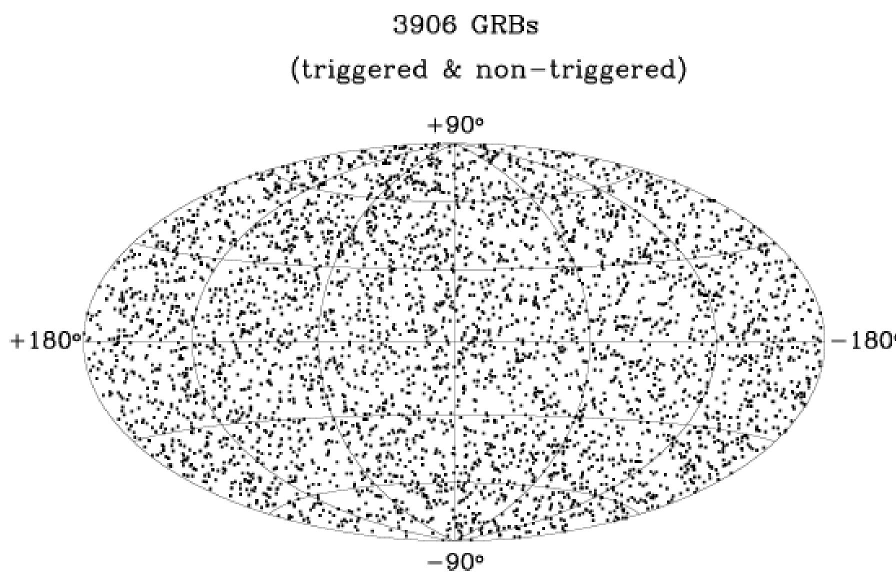
Slanted story. Seemingly diverse astronomical objects may be different views of galactic cores.

Gamma-Ray Bursts

- For short period of times, ~ seconds
  - GRB have a bimodal distribution of duration; accordingly, they are classified as “long” or “short”

  a source emits more energy in Gamma ray than the rest of the Universe
- Long GRBs are thought to come from a hypernova (an old star of large mass), or a core-collapse supernova. There is a prevailing consensus that the basic mechanism of GRB emission is an expanding relativistic fireball, with the beamed radiation due to shock waves. No direct confirmation that they are CR emitters
- During the abrupt compression the magnetic field could be squeezed to extremely large values, of the order of 10^{12}G to 10^{14}G, in a radius of some tens of kilometers



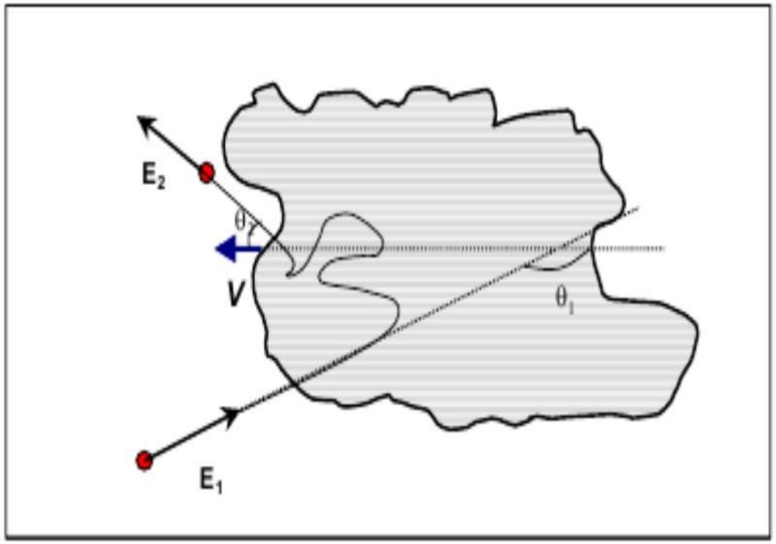


END OF 1ST LECTURE

Acceleration mechanism

Fermi 2nd order (1949)

particles accelerated in stochastic collisions with massive interstellar clouds (collisions to a moving diffusive wall!)



In the cloud reference frame

$$E_1^* = \gamma\, E_1 (1 - \beta \cos\theta_1)$$
$$E_2^* = E_1^*$$

Back to the Lab reference frame

$$E_2 = \gamma\, E_2^* \,(1 + \beta \cos\theta_2^*)$$

Then:

$$\frac{\Delta E}{E} = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2^* - \beta^2 \cos\theta_1 \cos\theta_2^*}{1 - \beta^2} - 1$$

But:

$$\langle \cos\theta_2^* \rangle = 0$$

$$\langle \cos\theta_1 \rangle = \frac{\int_{-1}^{1} \cos\theta_1 (1 - \beta\cos\theta_1)\, d\cos\theta_1}{\int_{-1}^{1} (1 - \beta\cos\theta_1)\, d\cos\theta_1} = -\frac{\beta}{3}$$

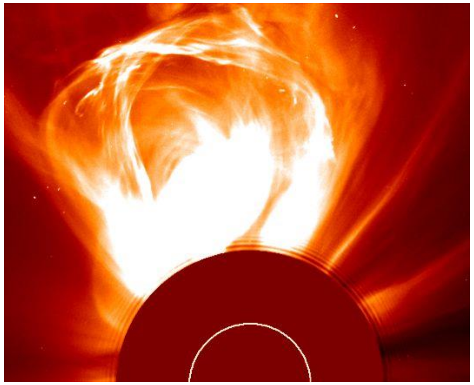
$$\left\langle \frac{\Delta E}{E} \right\rangle \simeq \frac{4}{3}\beta^2$$

$\beta \sim 10^{-4}$!!!

Acceleration mechanism

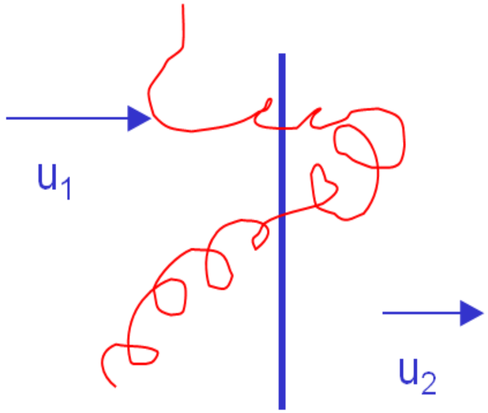
Fermi 1st order

Solar coronal mass ejection 9 Mar 2000



Shock formation :

- Sudden release of Energy (CMEs, SNRs, GRBs,…)
- Supersonic flow hits an obstacle (AGNs jets, pulsar winds, …)



Particles gain energy by consecutive crossings of the shock front!

$$\frac{\Delta E}{E} = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2^* - \beta^2\cos\theta_1\cos\theta_2^*}{1-\beta^2} - 1$$

Now (plane shock front):

$$\langle\cos\theta_1\rangle = \frac{\int_{-1}^{0}\cos^2\theta_1\, d\cos\theta_1}{\int_{-1}^{0}\cos\theta_1\, d\cos\theta_1} = -\frac{2}{3}$$

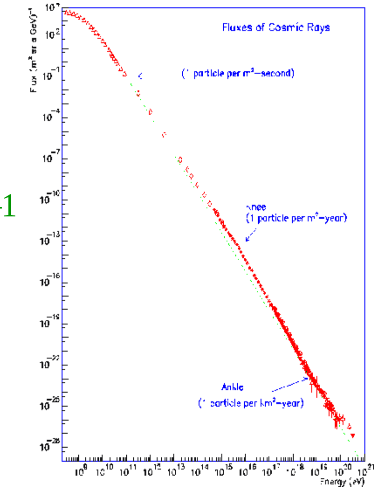
$$\langle\cos\theta_2^*\rangle = \frac{\int_{0}^{1}\cos^2\theta_2^*\, d\cos\theta_2^*}{\int_{0}^{1}\cos\theta_2^*\, d\cos\theta_2^*} = \frac{2}{3}$$

$$\left\langle\frac{\Delta E}{E}\right\rangle \simeq \frac{4}{3}\beta$$

The power law

$$\frac{dN}{dE} \propto E^{-\gamma}$$

$$(N > E) \propto E^{-\gamma+1}$$



In each cycle the particle gains a small fraction of energy ε. After n cycles:

$$E_n = E_0 (1+ \varepsilon)^n$$

Or the number of cycles to attain an energy E is:

$$n = \ln(E/E_0)/\ln(1+\varepsilon)$$

The particle may escape from the shock region with some probability P_i .Then the probability to escape with $E>E_n$ is:

$$P_{E_n} = P_i \sum_{j=n}^{\infty} (1 - P_i)^n = (1 - P_i)^n$$

and

$$\frac{N}{N_0} = P_{E_n} = \left(\frac{E}{E_0}\right)^{-\alpha}$$

$$\alpha = -\frac{ln(1 - P_i)}{ln(1 + \varepsilon)} \cong \frac{P_i}{\varepsilon}$$

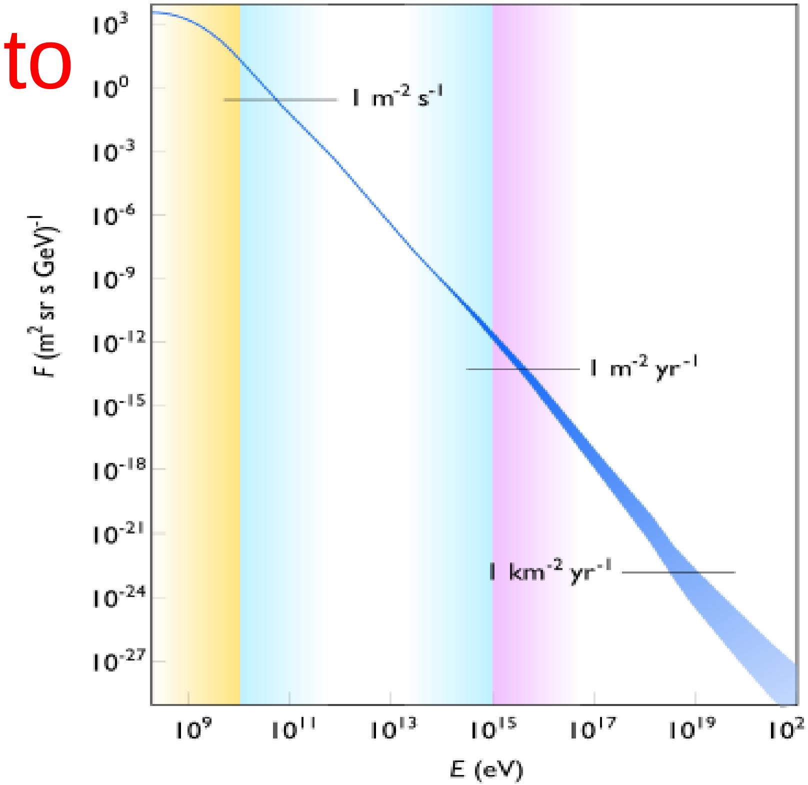
$$\boxed{\left(\frac{dN}{dE}\right)_{Source} \approx E^{-2}}$$

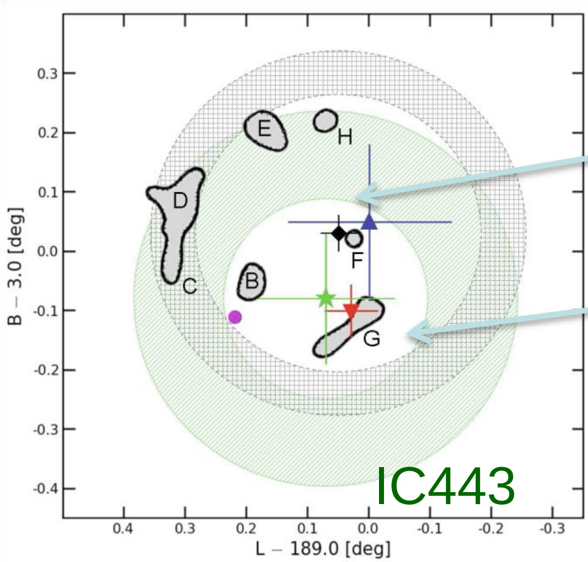
$$\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-\gamma}$$

$$\boxed{\left(\frac{dN}{dE}\right)_{Earth} \propto \left(\frac{dN}{dE}\right)_{Source} .\tau_{esc}(E) \propto E^{-2.7}}$$

Proof of the origin of CR up to almost the knee

- Evidence that SNR are sources of CR up to ~1000 TeV (almost the knee) came from morphology studies of RX J1713-3946 (H.E.S.S. 2004) with photons
- Striking evidence from the morphology of SNR IC443 (MAGIC + Fermi/Agile 2010)



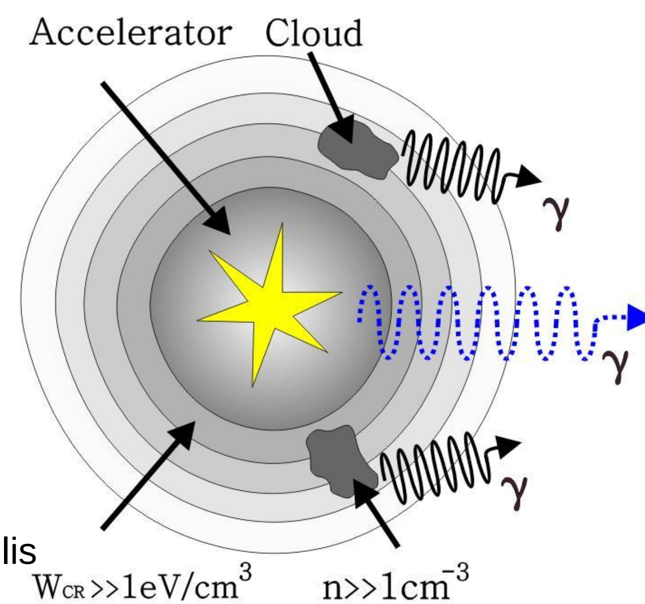


Fermi,

Egret

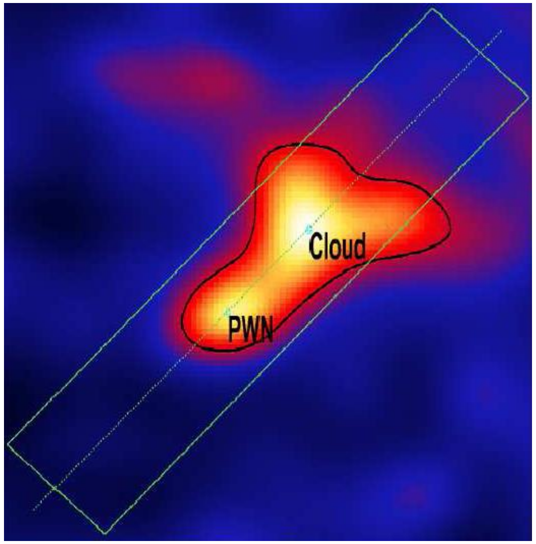
Magic,

Veritas

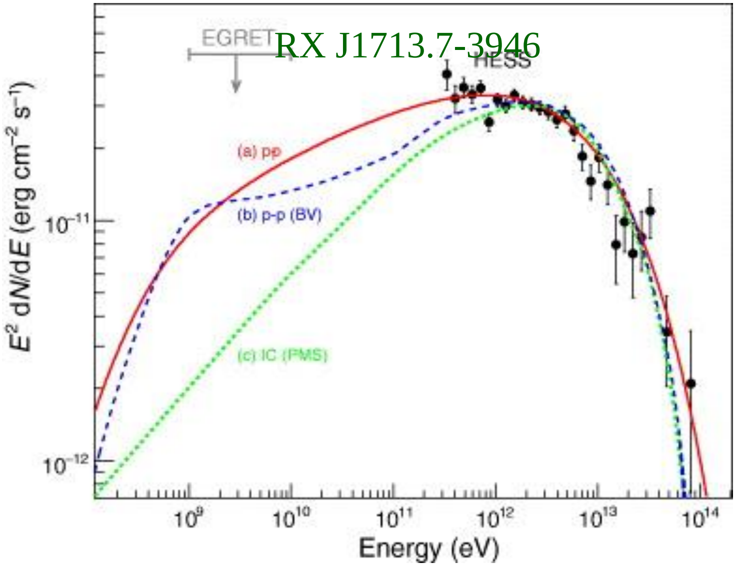


Molecular clouds close to IC 443, W51, RX J1713.7-3946

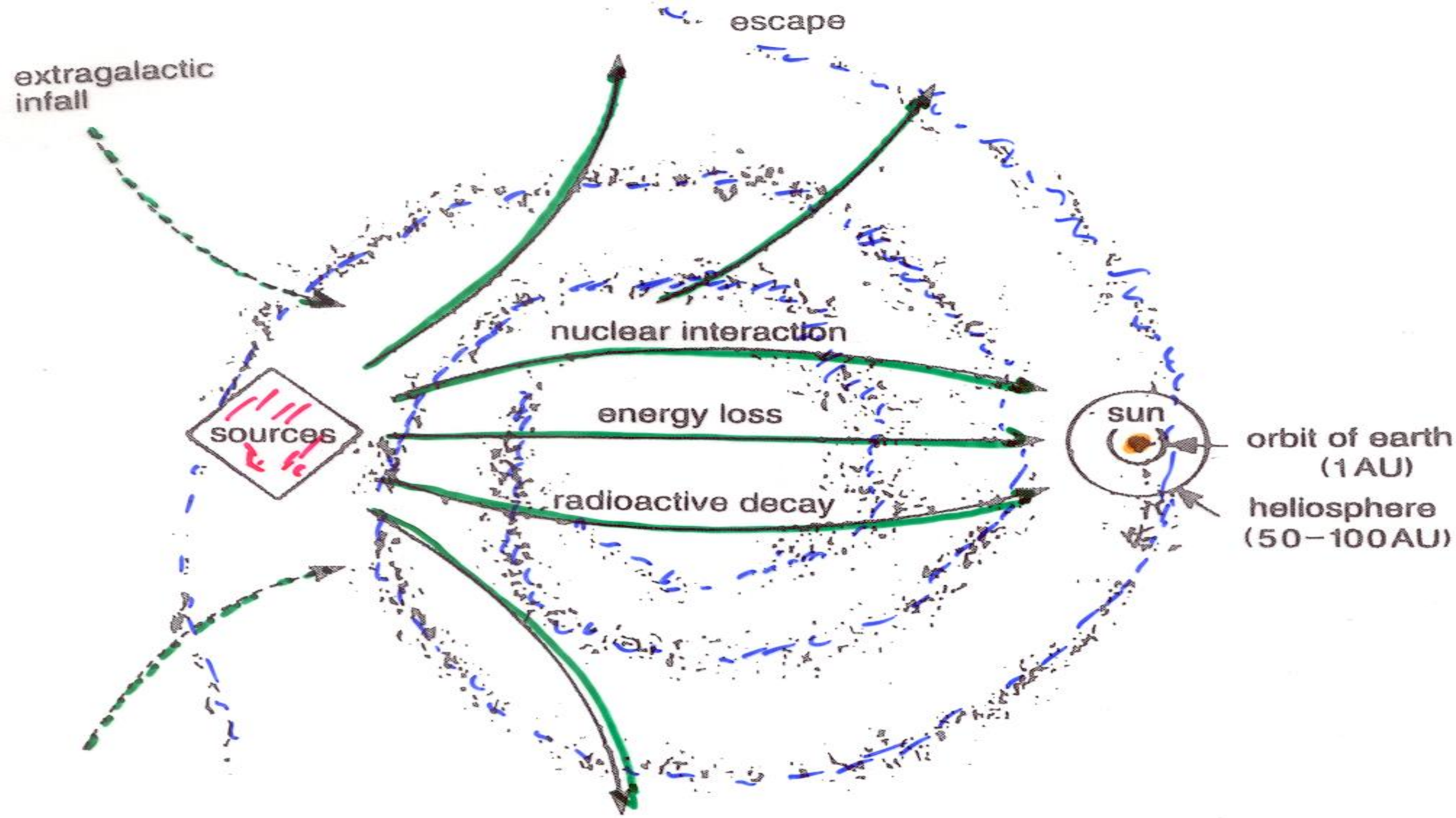
• VHE γ-ray excess compatible with cloud



• Differential energy spectrum prefers π^0 production

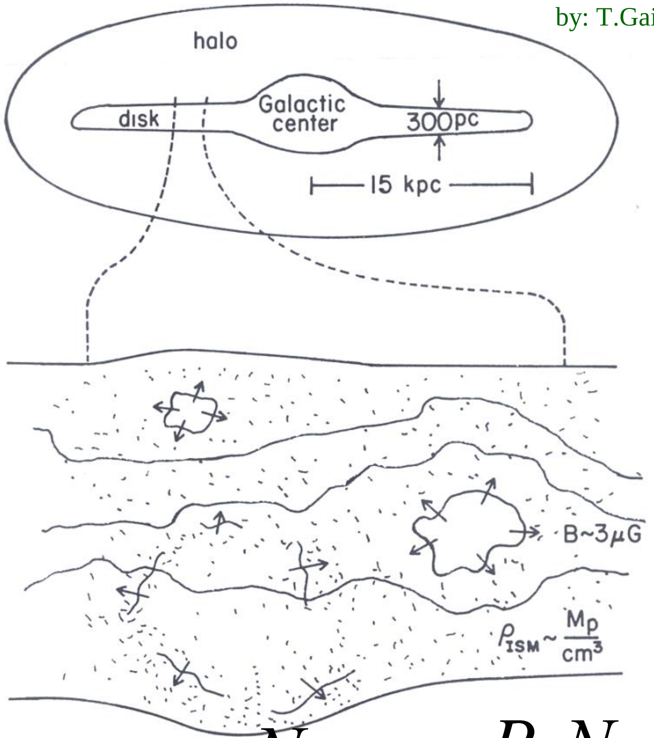


The propagation



Propagation

by: T.Gaisser



Charged cosmic rays diffuse and interact in the Galactic randomly magnetized ISM . Confinement times are quite long ($\tau \sim 10^7$ years) and directions become basically isotropic.

Transport equation :

$$\frac{\partial N_i}{\partial t} = Q_i + \overline{\nabla} \bullet \left(D\, \overline{\nabla} N_i - \overline{V} N_i \right) + \frac{\partial}{\partial E}\left(b(E) N_i \right) - \frac{N_i}{\tau_i} - \sum_{j>i} \frac{P_{ji} N_j}{\tau_j}$$

Sources

Diffusion

Convection

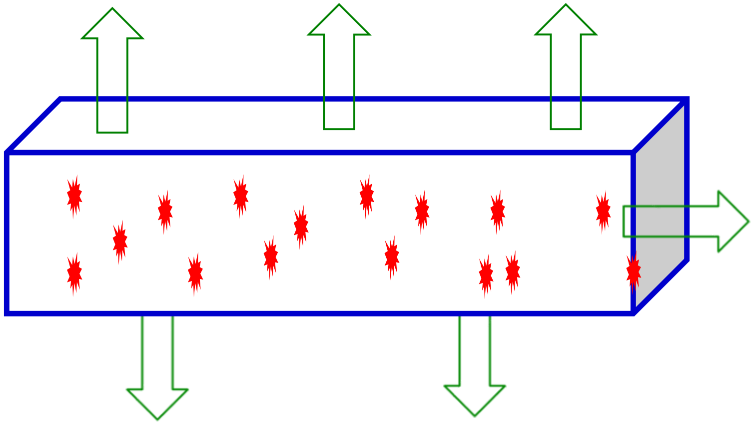
Energy gains and losses

Spallation and decay losses

Spallation gains

Leaky-Box

A box where charged cosmic rays freely propagates having however some probability to escape by the walls. The sources are uniformely distributed.



Simplified stationary equation :

$$\boxed{0 = \underbrace{Q_i}_{\text{Sources}} + \sum_{j>i} N_j \left\{ \rho\beta c\, \sigma_{ji}^{spall} + \frac{1}{\gamma\tau_{ji}^{decay}} \right\} - N_i \left\{ \rho\beta c\, \sigma_i^{spall} + \frac{1}{\gamma\tau_i^{decay}} + \frac{1}{\tau_i^{esc}} \right\}}$$

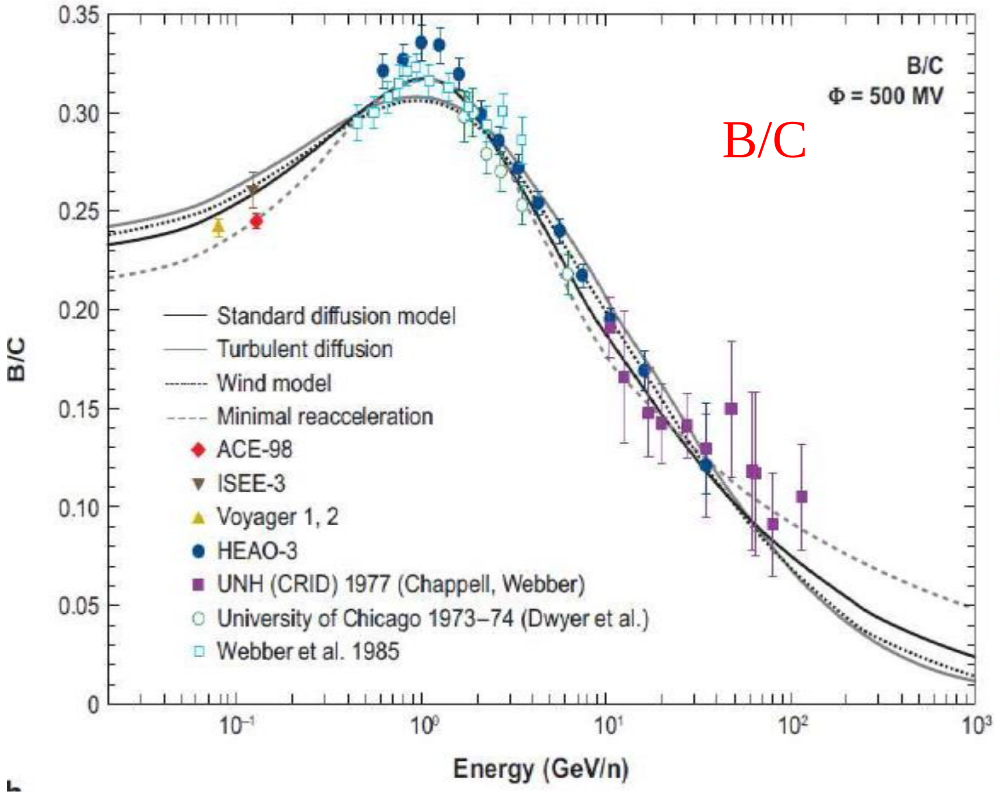
Sources

Spallation and decays gains

Spallation, decays and escape losses

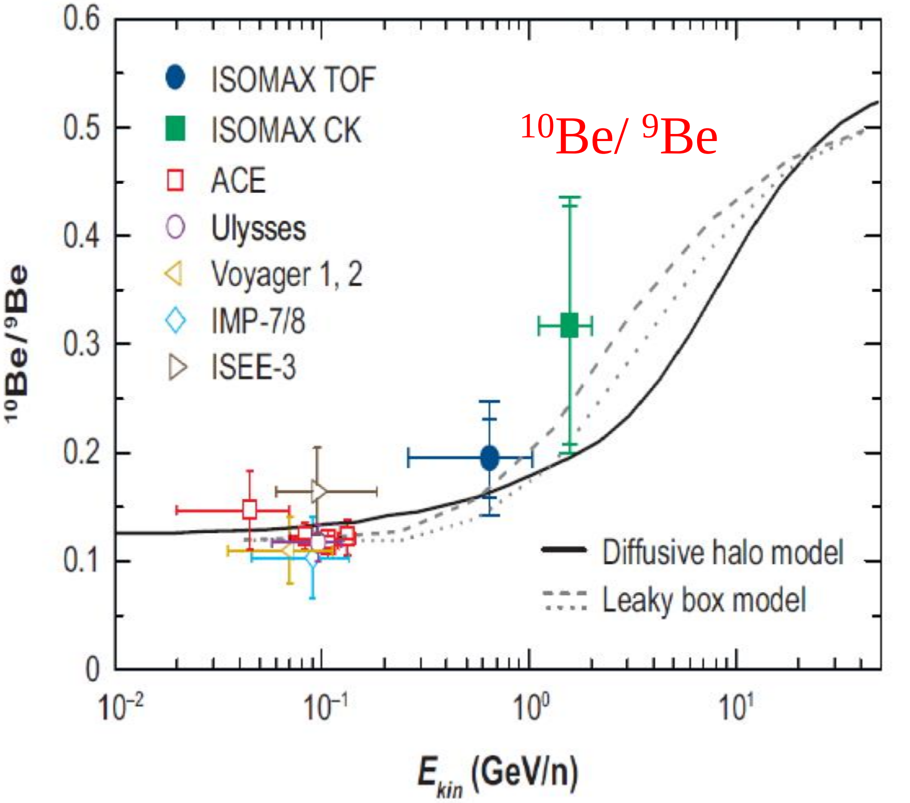
Constraining propagation models

Secondary/primary ratios



Box size, Diffusion coef., escape time, ...

Unstable/stable isotopos

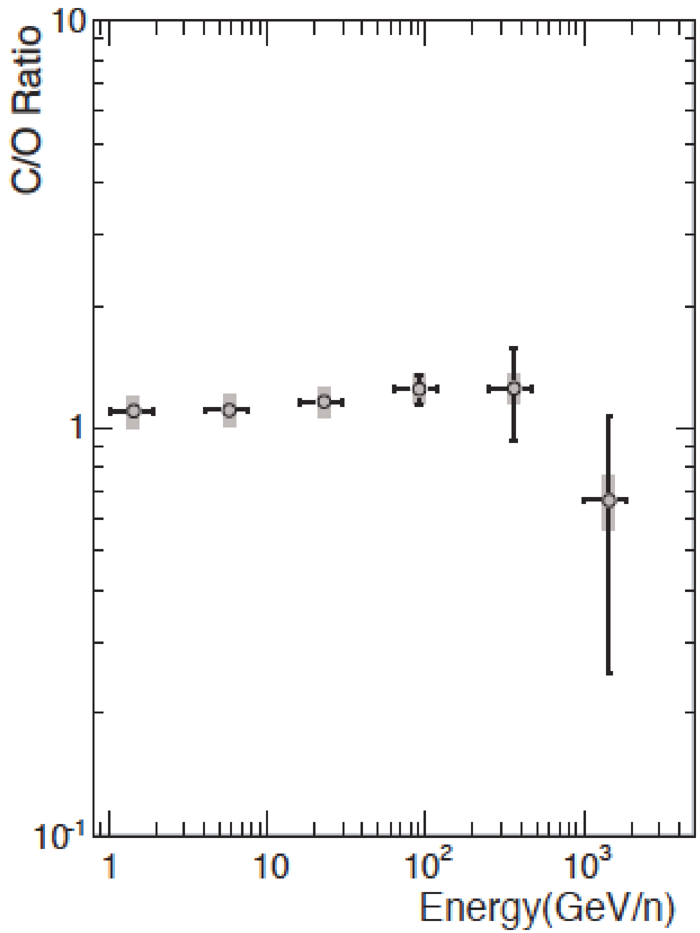


Radioactive clocks

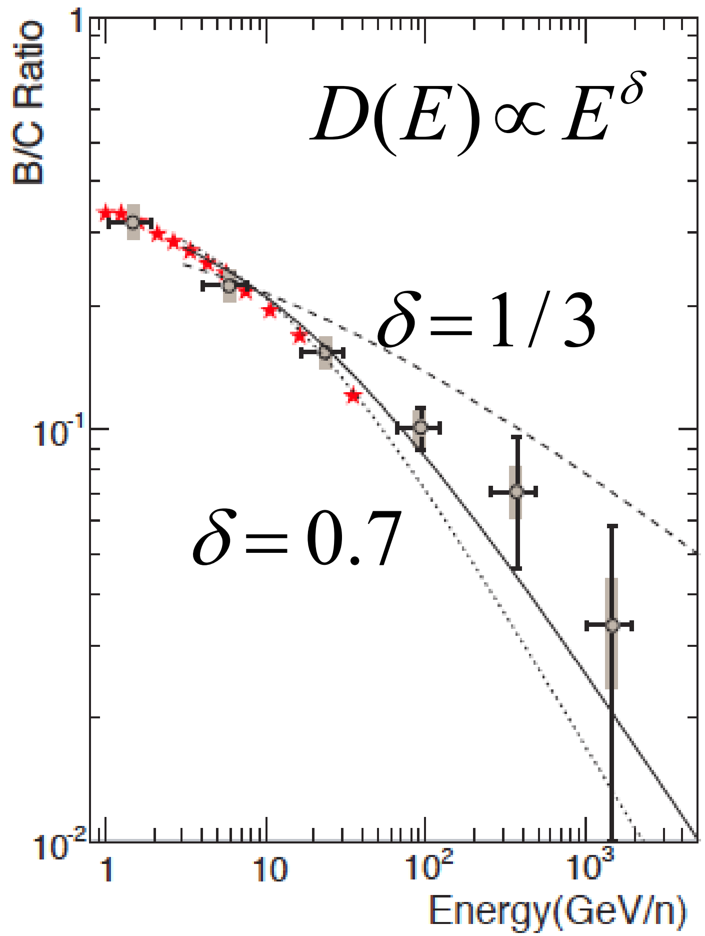
Energy dependence (τ_{esc})

CREAM 2008

Primary/Primary



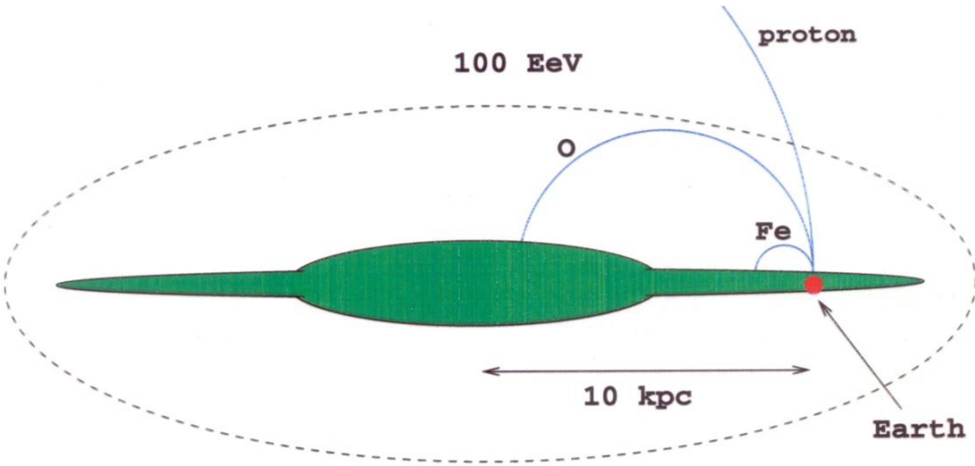
Secondary/Primary



Confinement and composition

Magnetic Field:

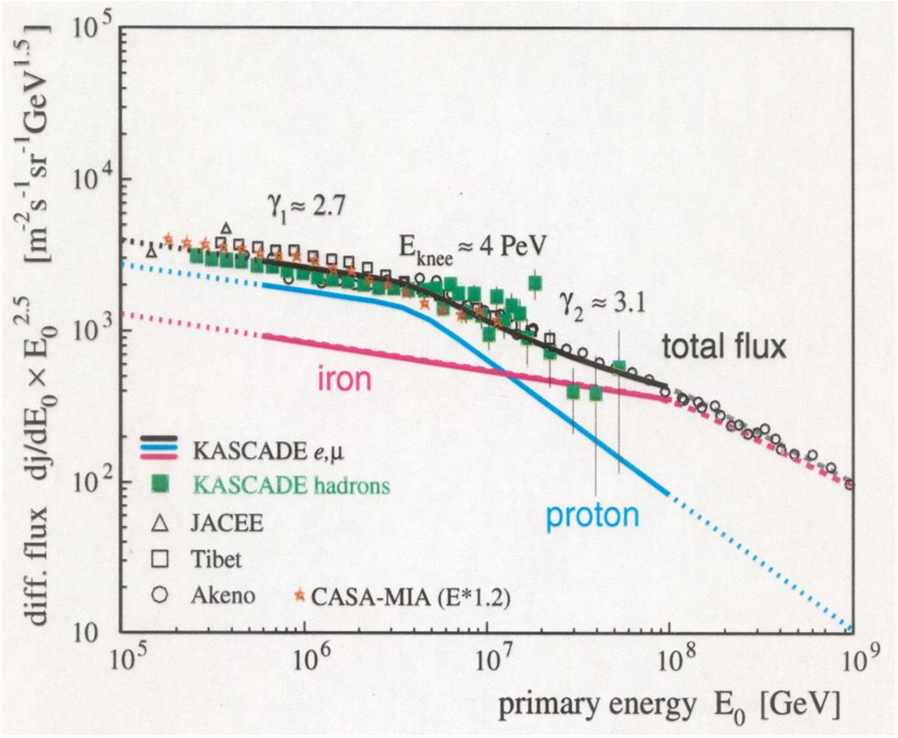
- Galactic ~1-3 μG
- Intergalatic 1 nG > B > 1fG



Larmor Radius:

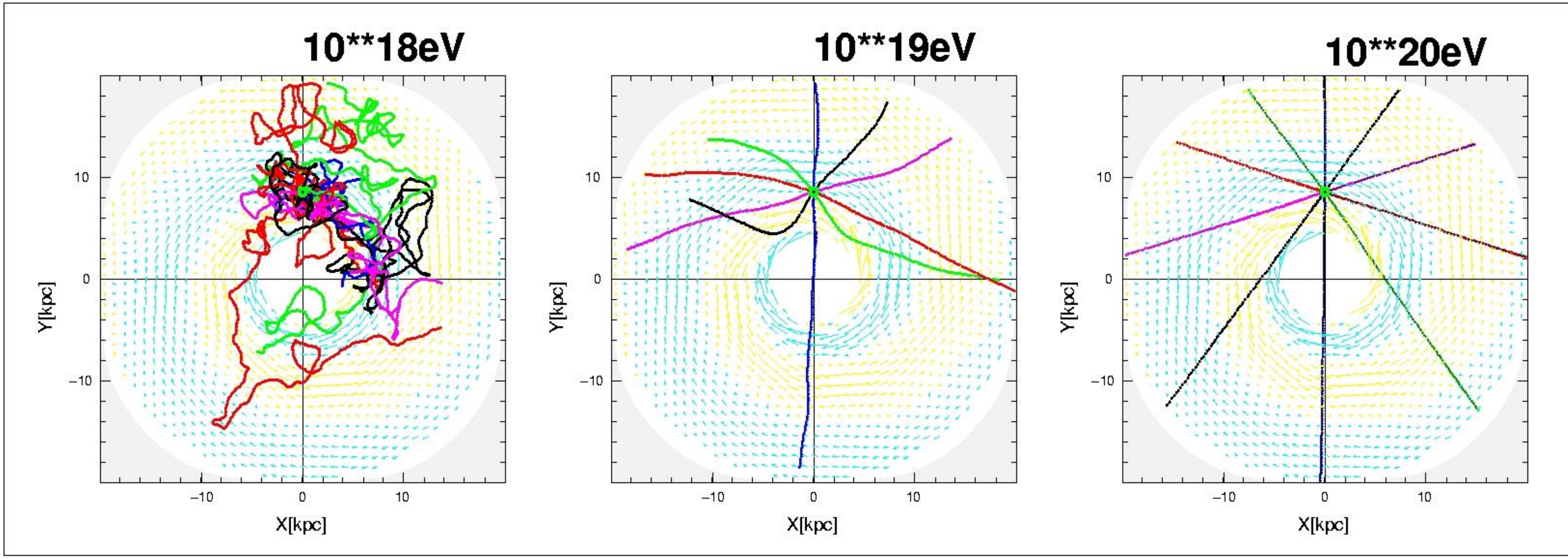
$$R = \frac{E}{ZeB}$$

Several knees?



Galactic Magnetic Field deflection (p)

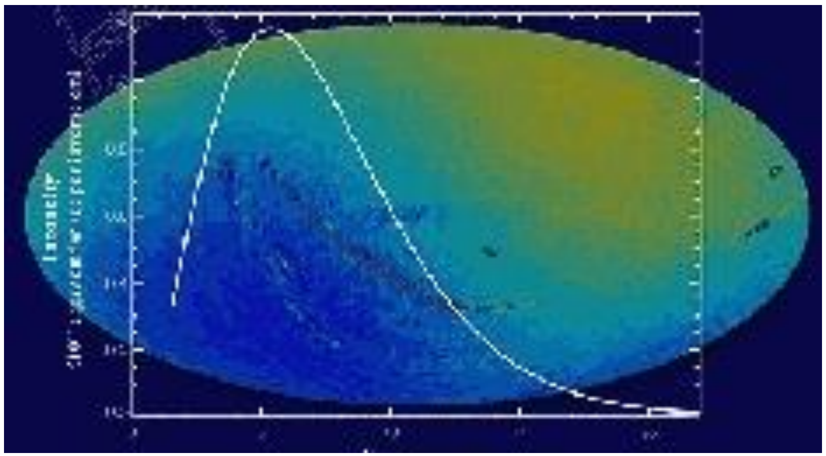
T.Stanev

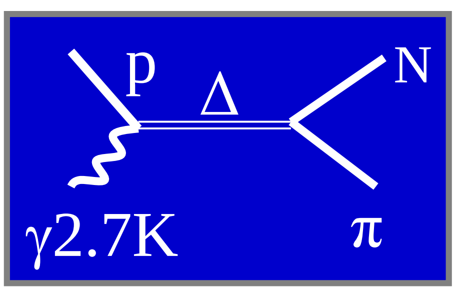


Above 10^{19} : Astronomy !

An unique opportunity to measure the galactic magnetic field ?

The Greisen-Zatsepin-Kuzmin (GZK) cutoff

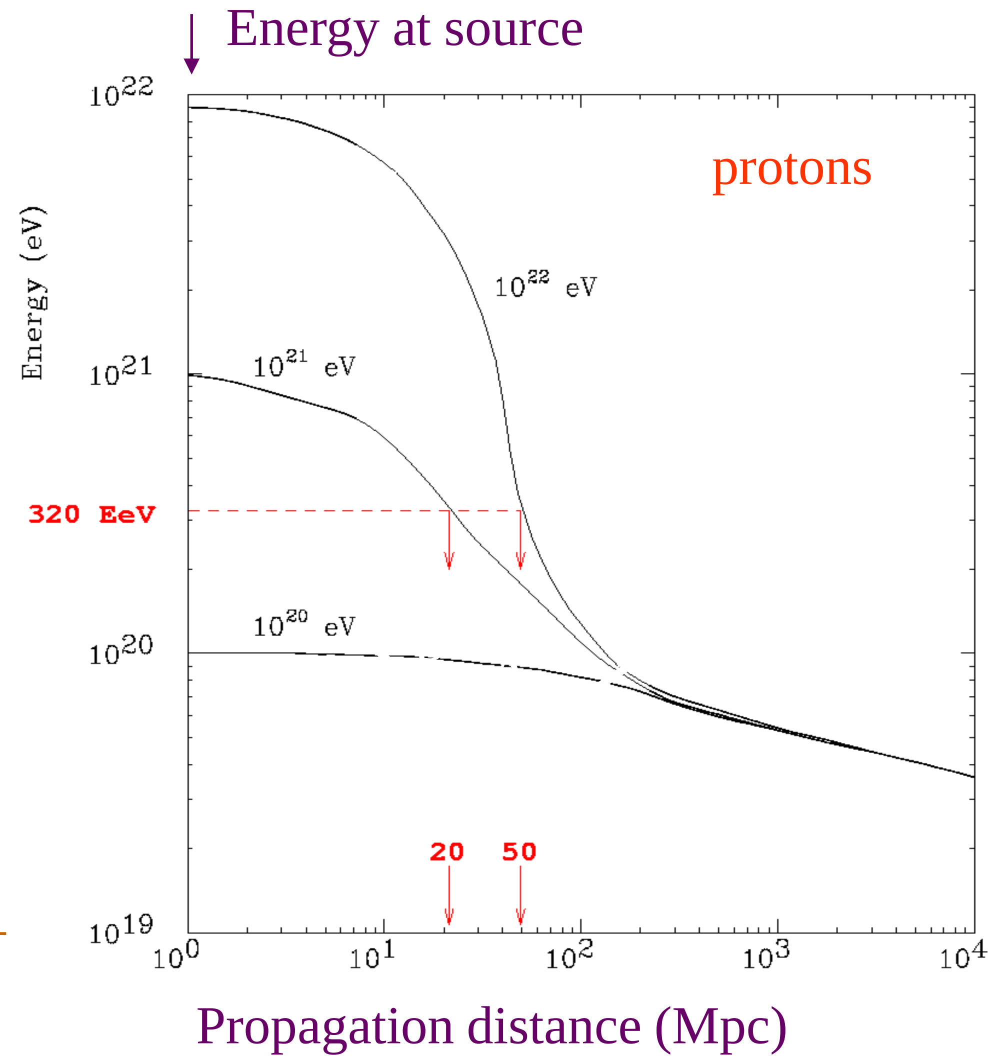




$E_p \approx 10^{20}\,\mathrm{eV}$

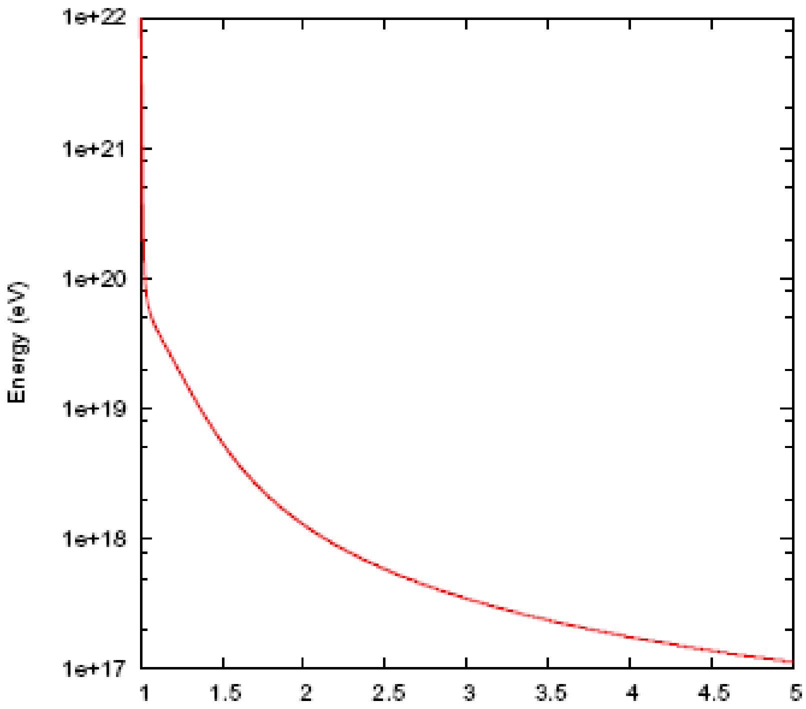
$$\lambda = \frac{1}{\sigma_{p\gamma}\,\rho_{CMB}}$$

$$\approx 6\ \mathrm{Mpc}$$



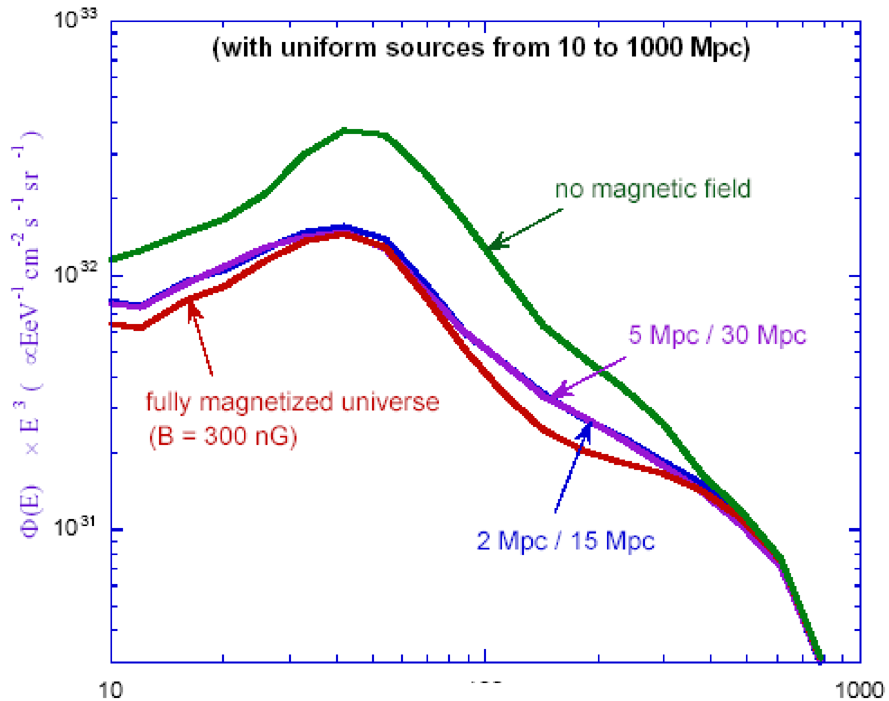
GZK is model dependent

GZK cutoff Energy – Stecker and Scully



1 + z

GZK and magnetic fields (protons)
Deligny, Parizot, Letessier-Selvon



Energy (in EeV)

Sources type and distribution

Primary composition

Magnetic fields

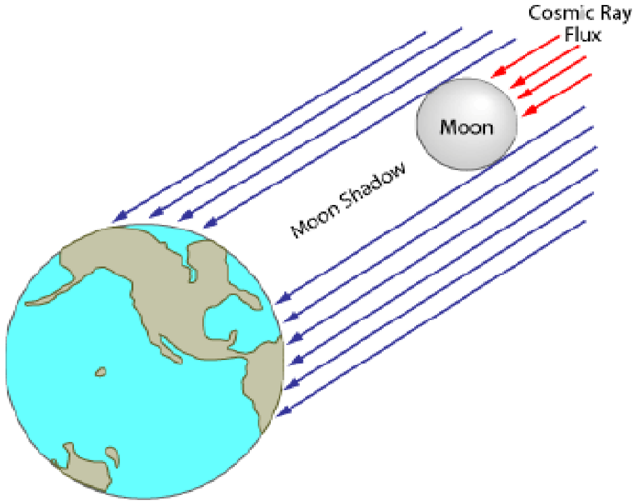
Not a true cutoff !

Pileup

Recovery of the spectrum at higher energies ?

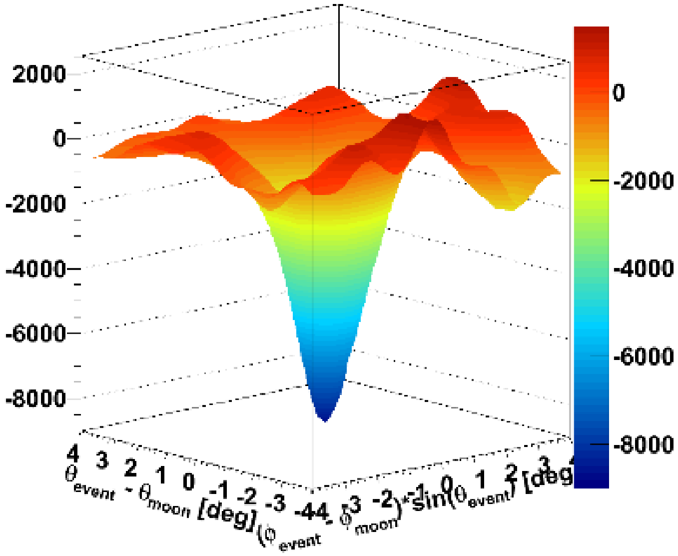
Interaction with the Solar System and the Earth

We see the Moon!

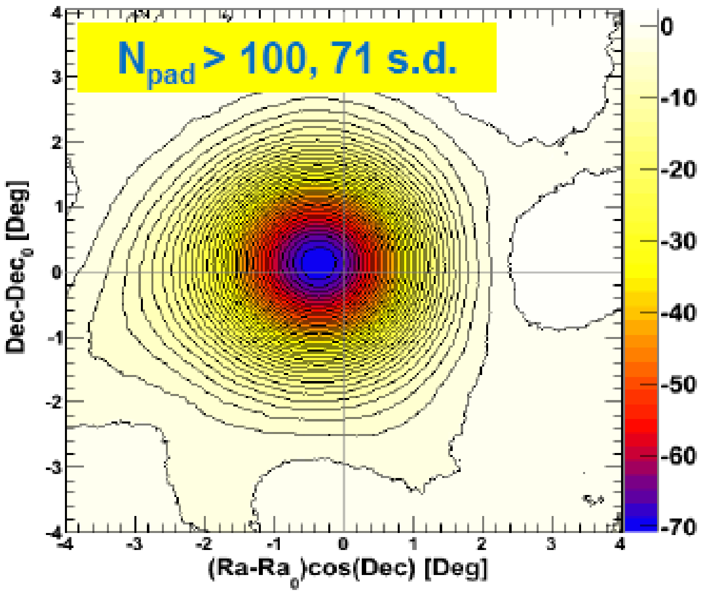


- Moon diameter 0.5°
- Angular resolution: < 1°

Ice Cube

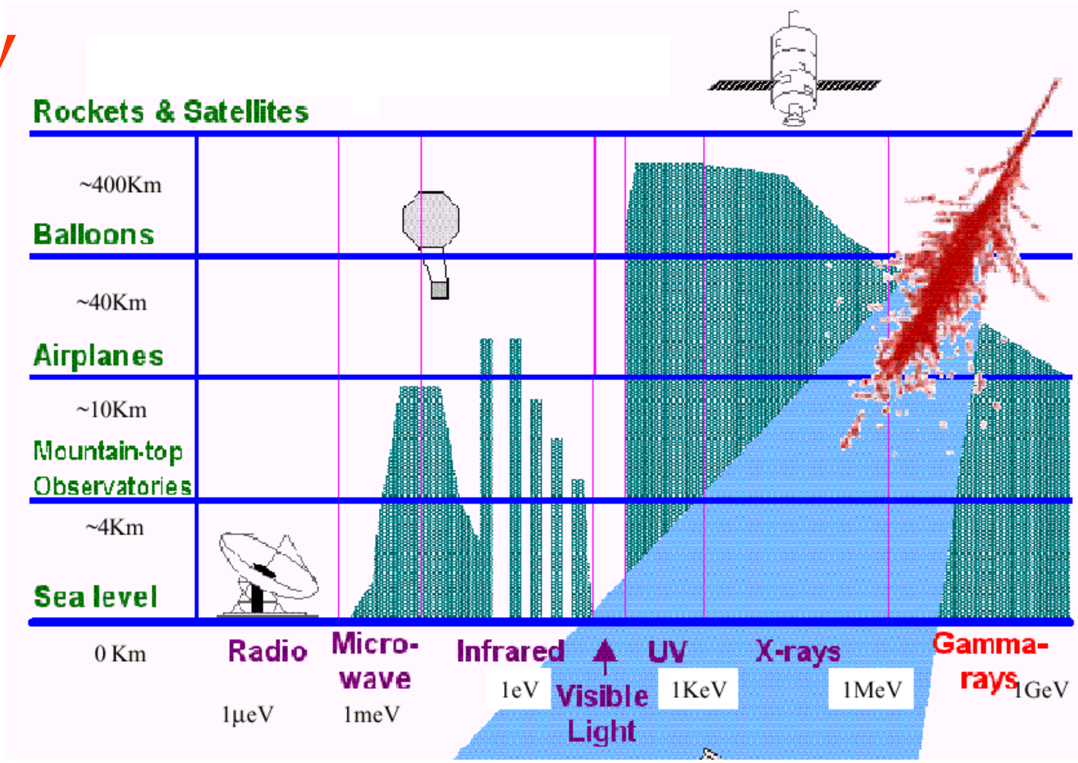


Argo-YBJ

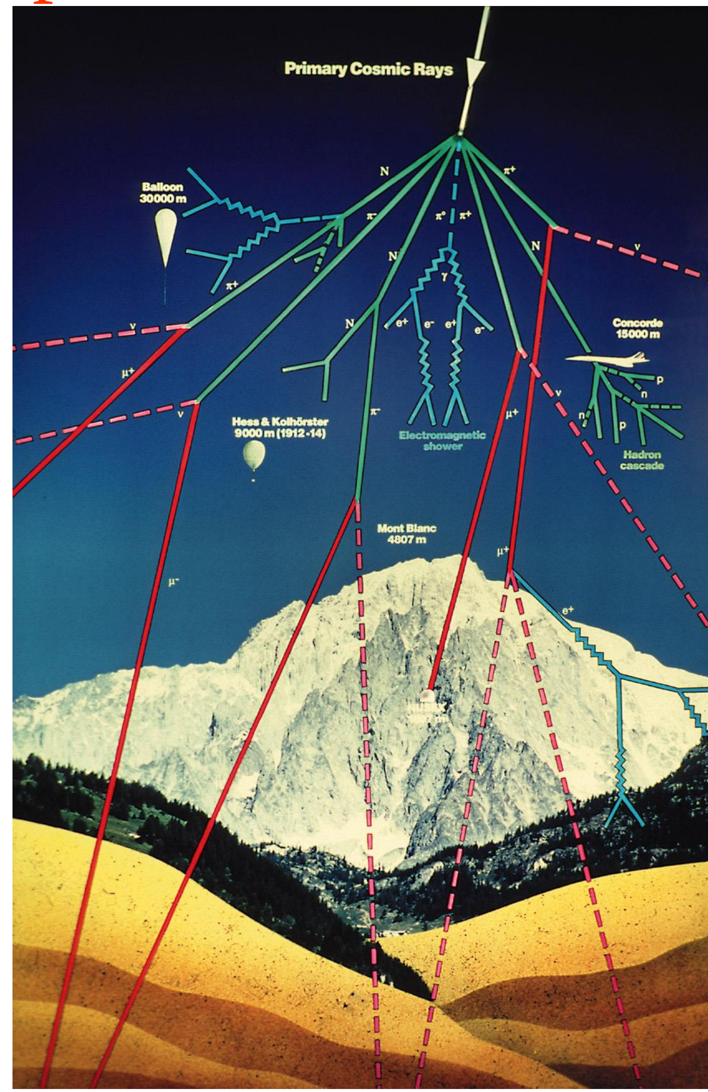


Interaction in the atmosphere/Earth

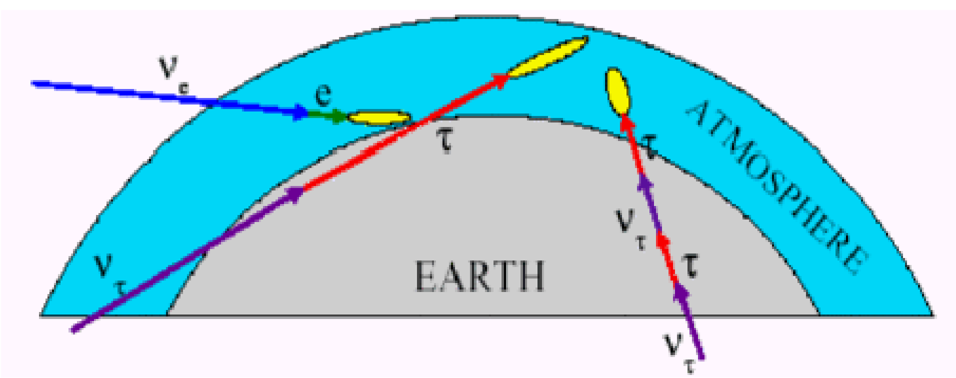
γ



p/nucleus



ν



Fluxes in the atmosphere

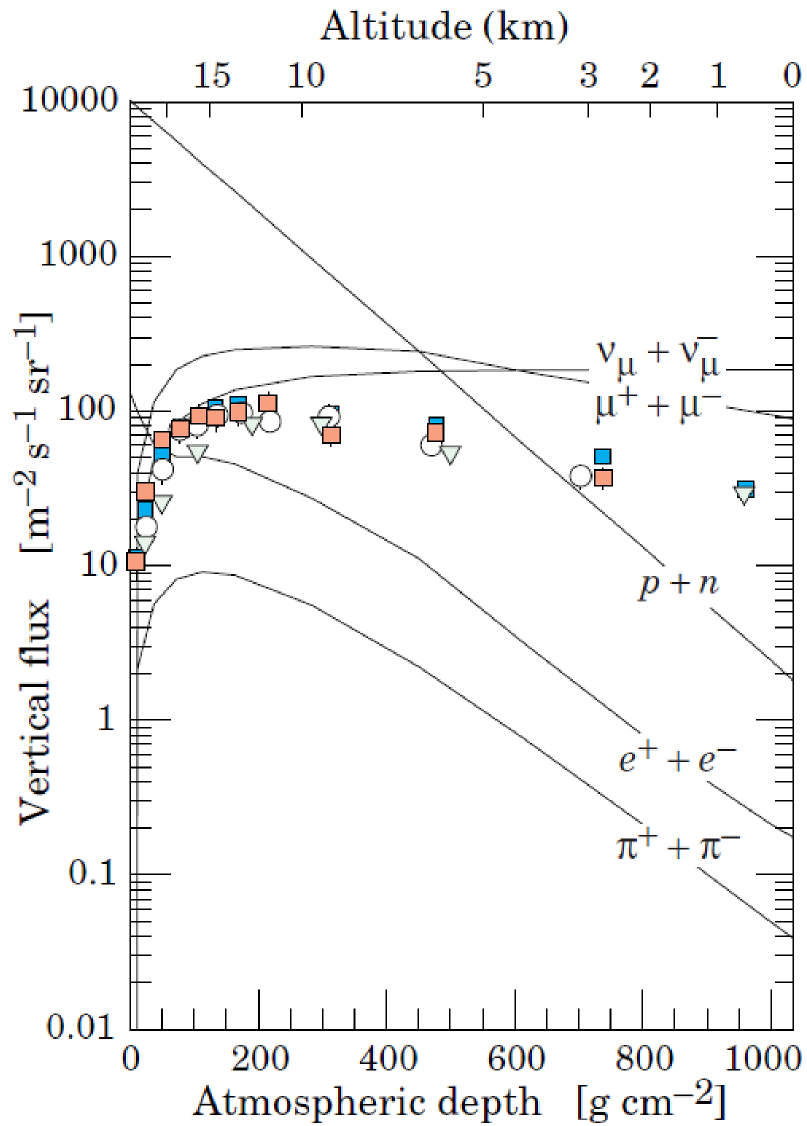
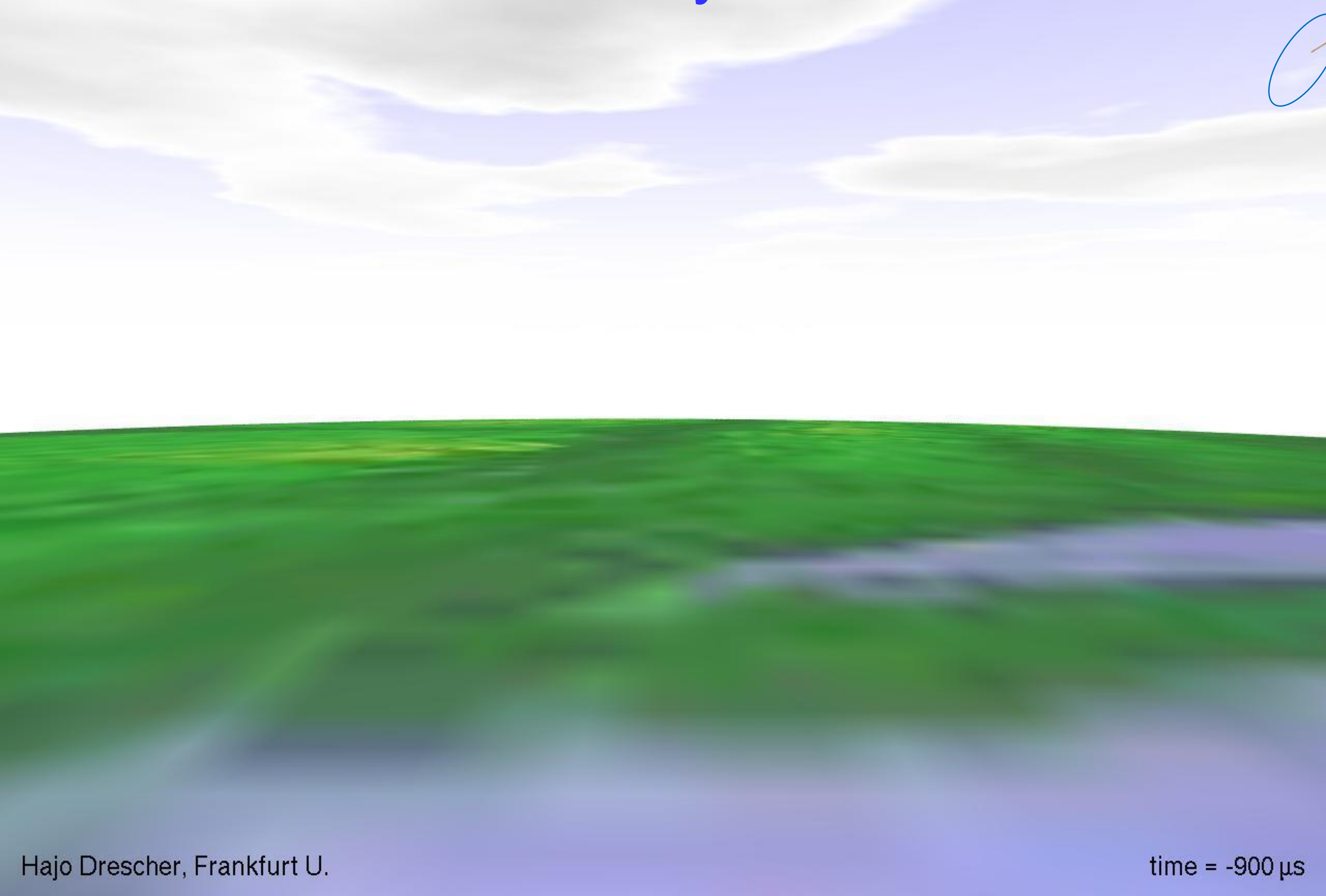


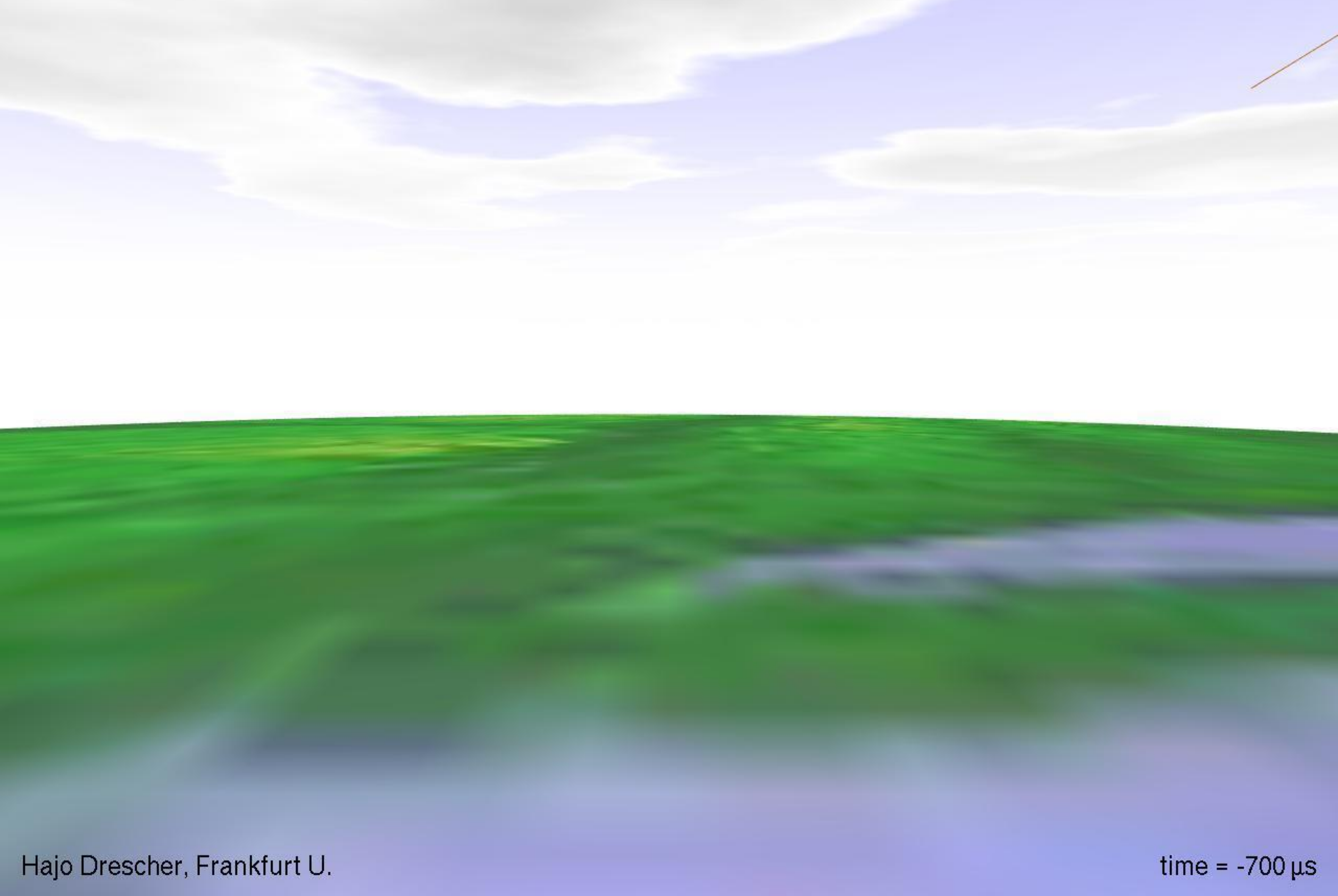
Figure 26.3: Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux of Eq. (26.2). The points show measurements of negative muons with $E_\mu > 1$ GeV [32–36]. **J. Beringer et al (PDG) PR D86 010001 (2012)**

The events: Cosmic rays "rain"

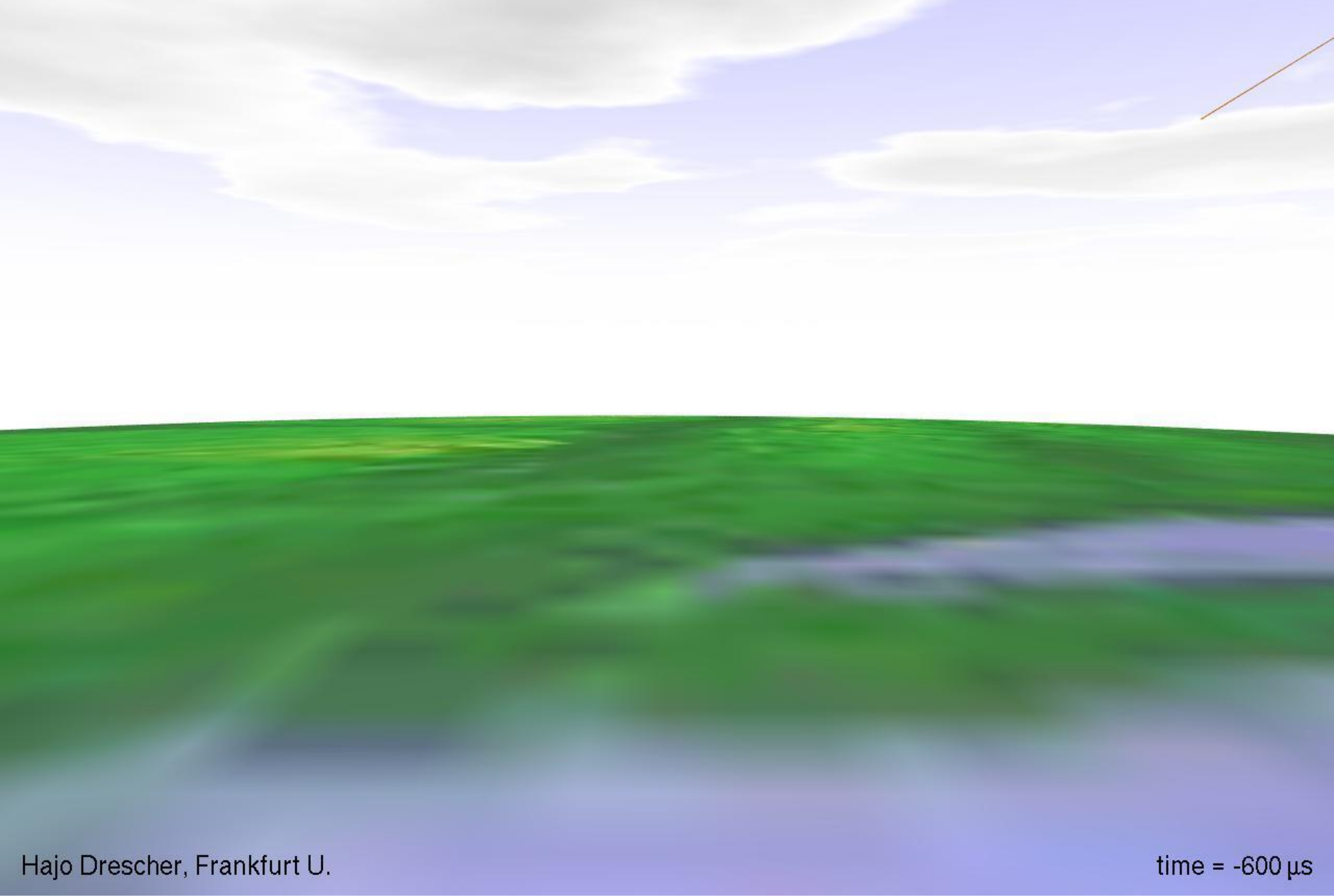


The events: Cosmic rays “rain”

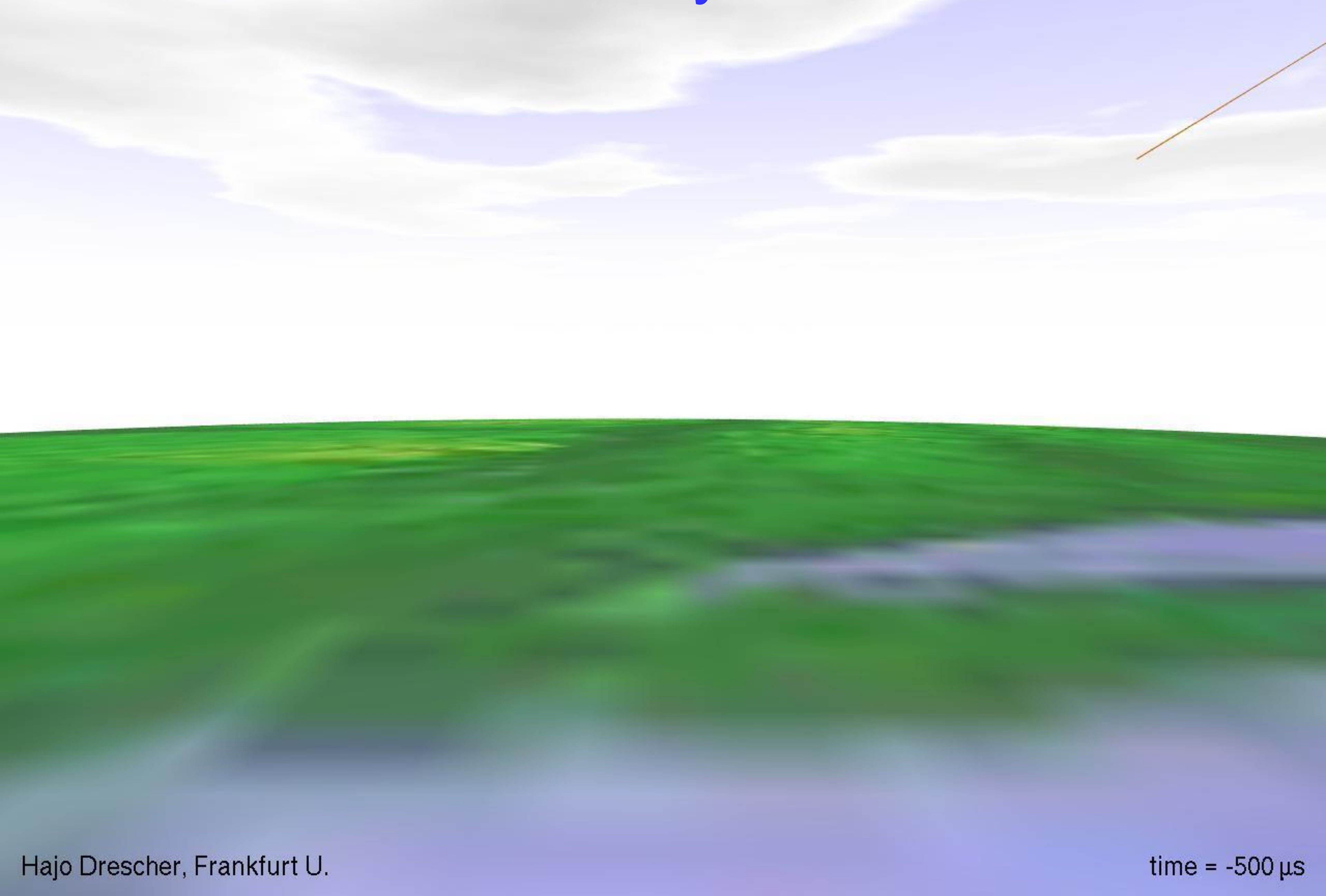
The events: Cosmic rays "rain"



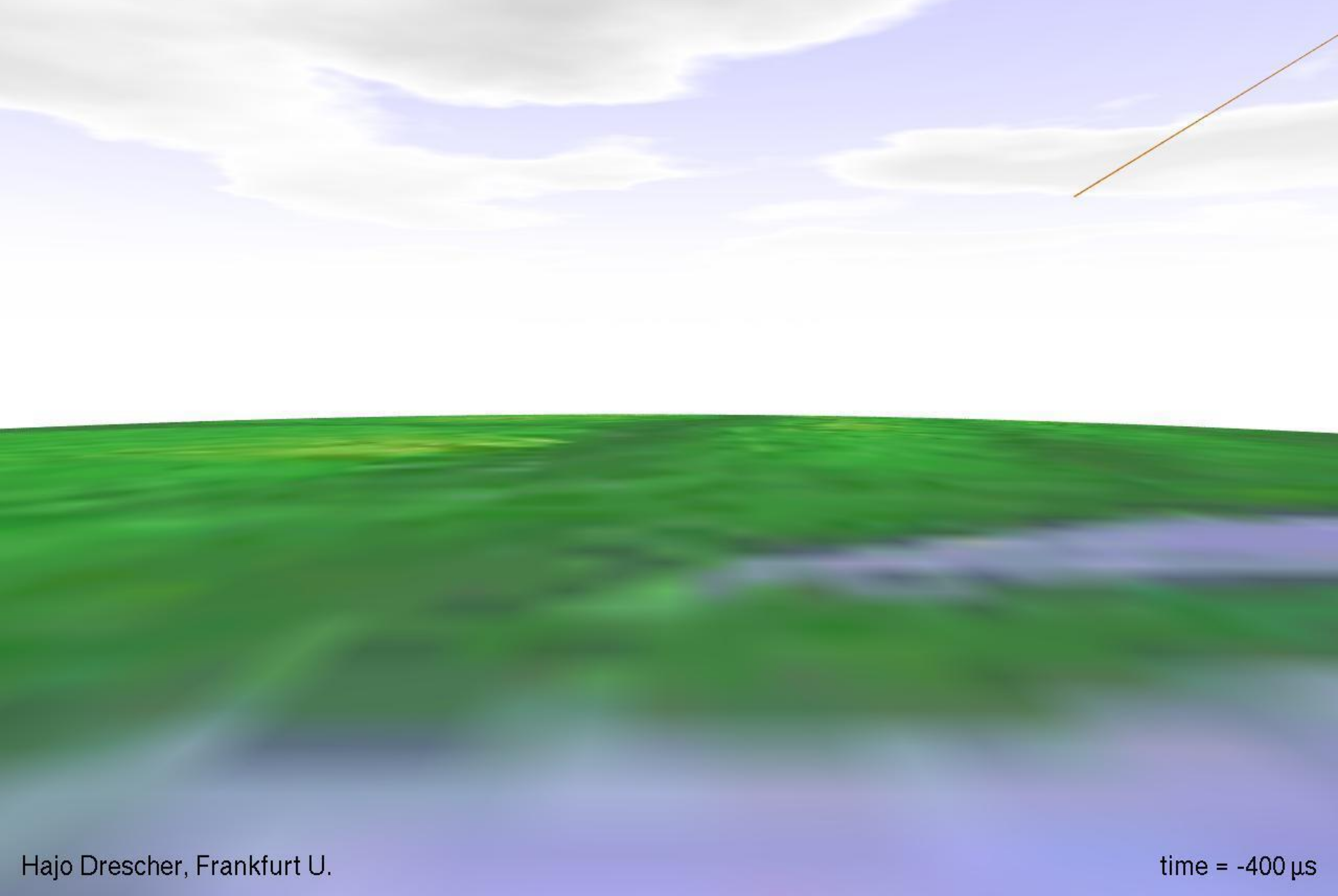
The events: Cosmic rays “rain”



The events: Cosmic rays “rain”

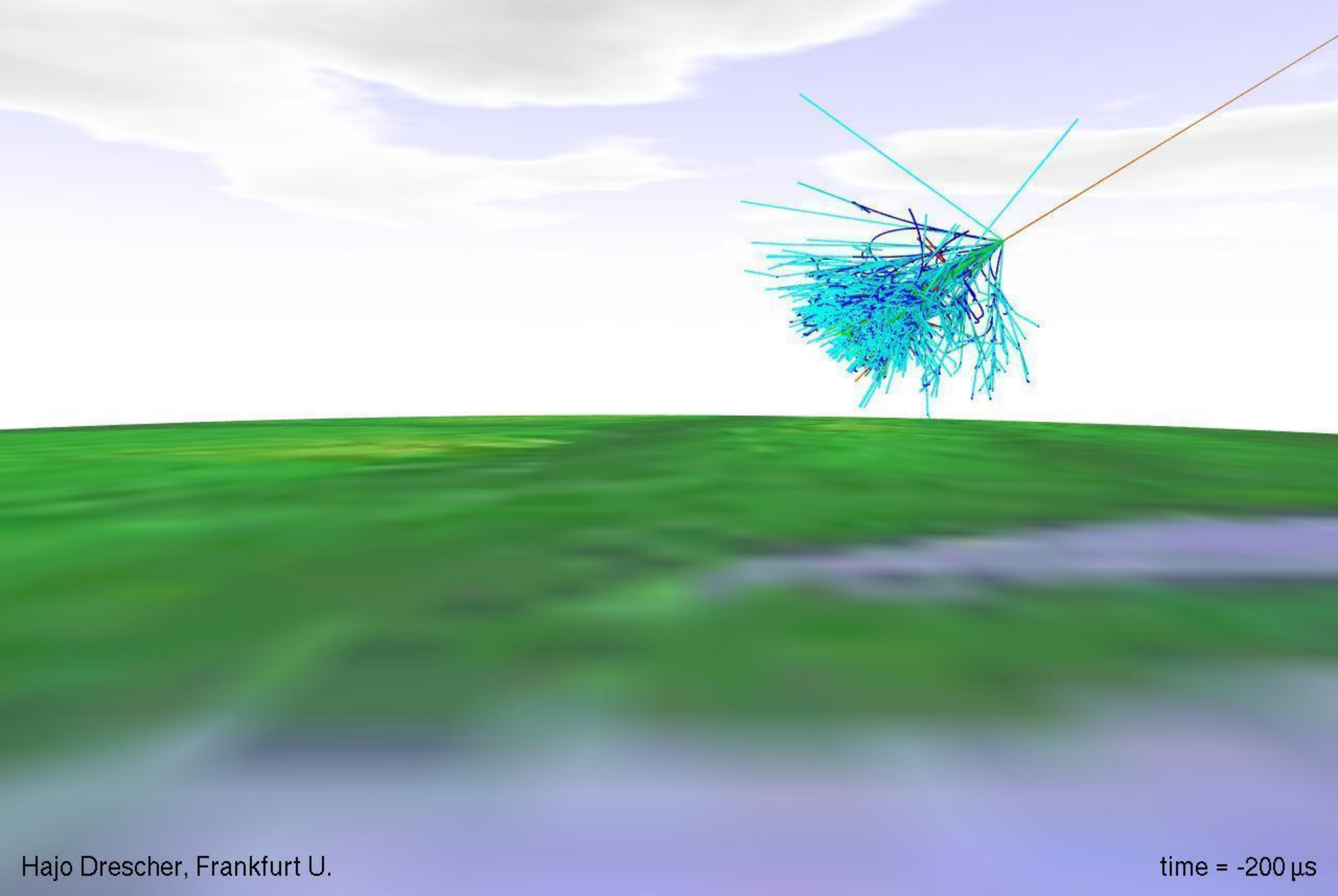


The events: Cosmic rays "rain"

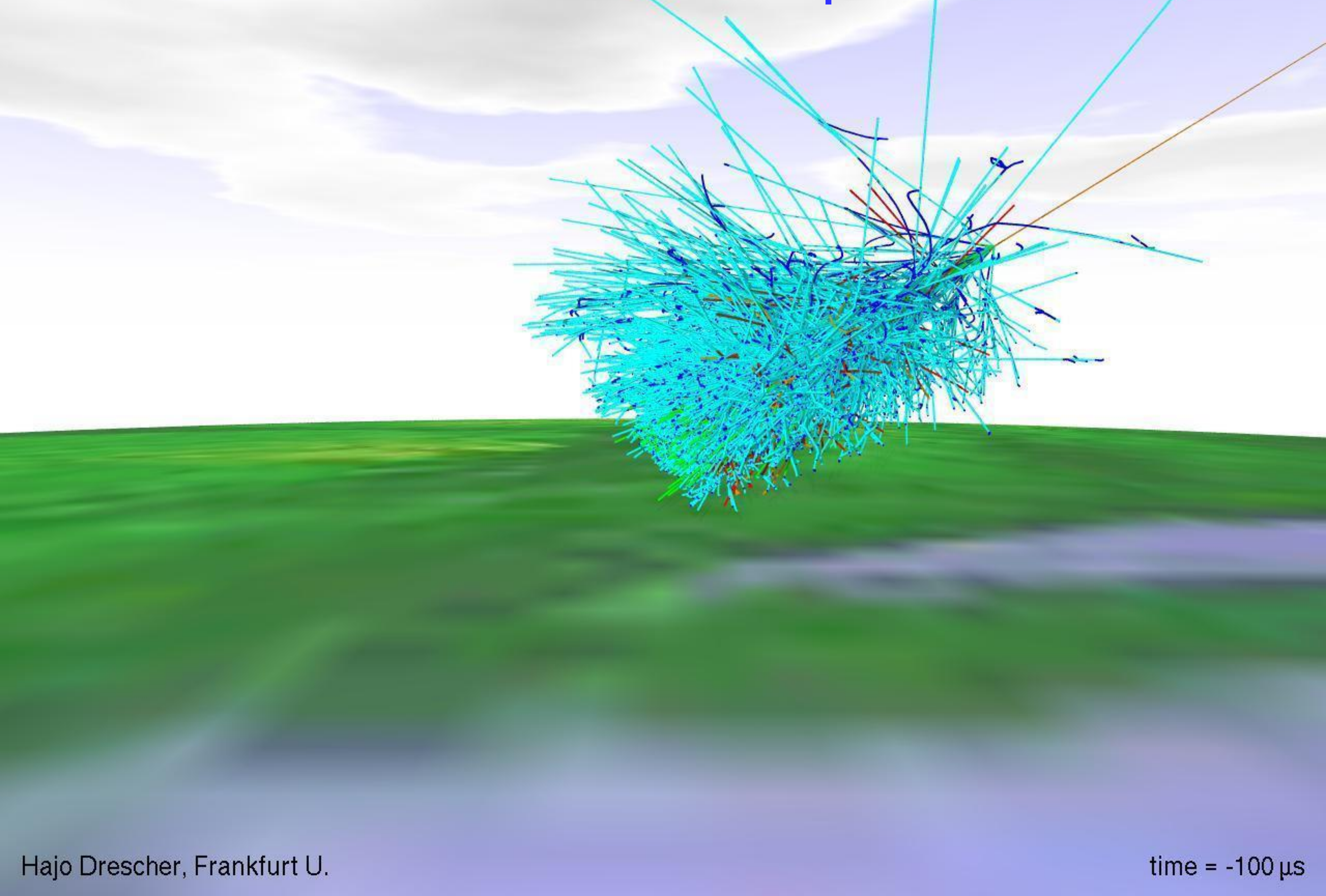


The events: first interaction

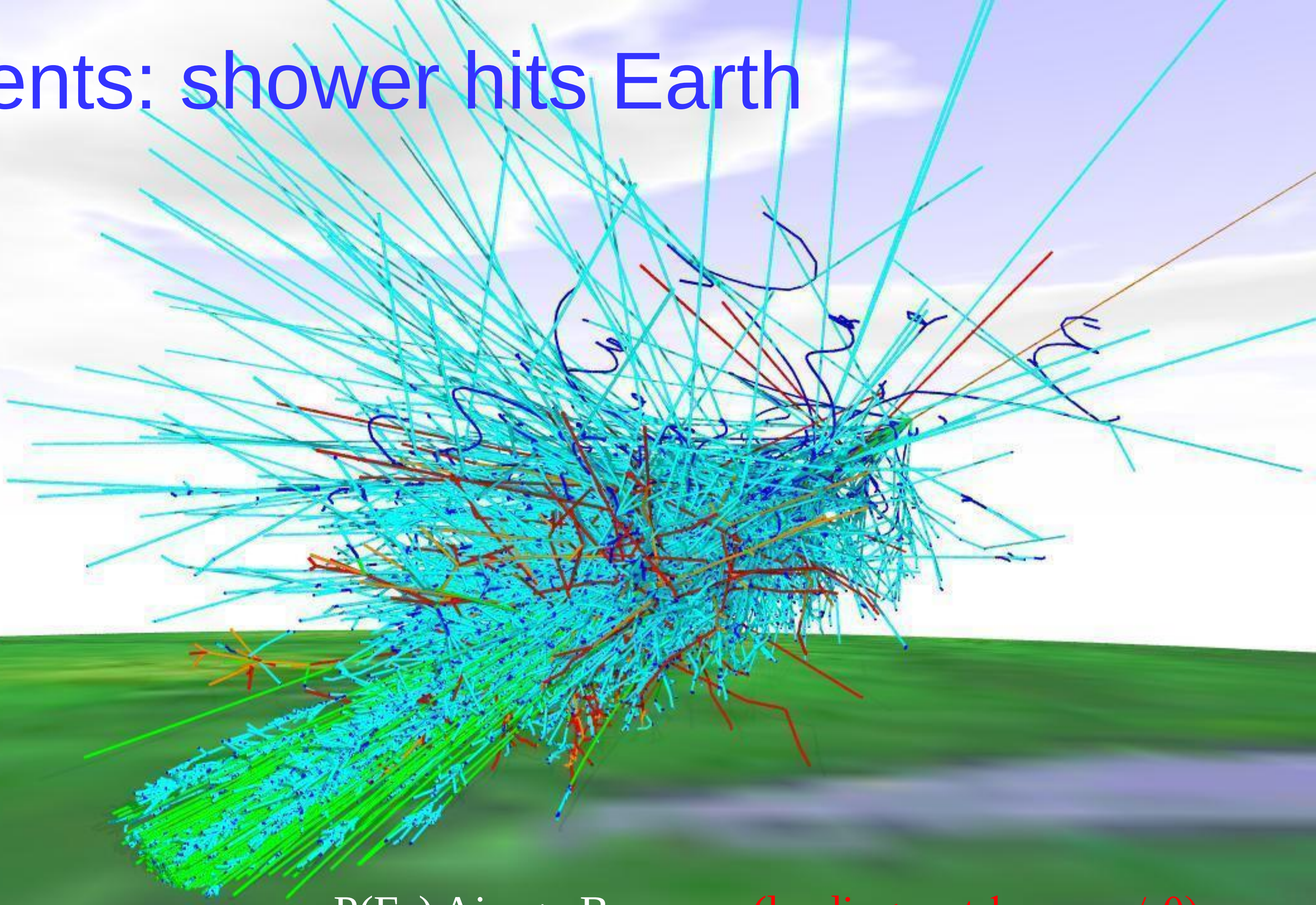
The events: shower development



The events: shower development



The events: shower hits Earth surface



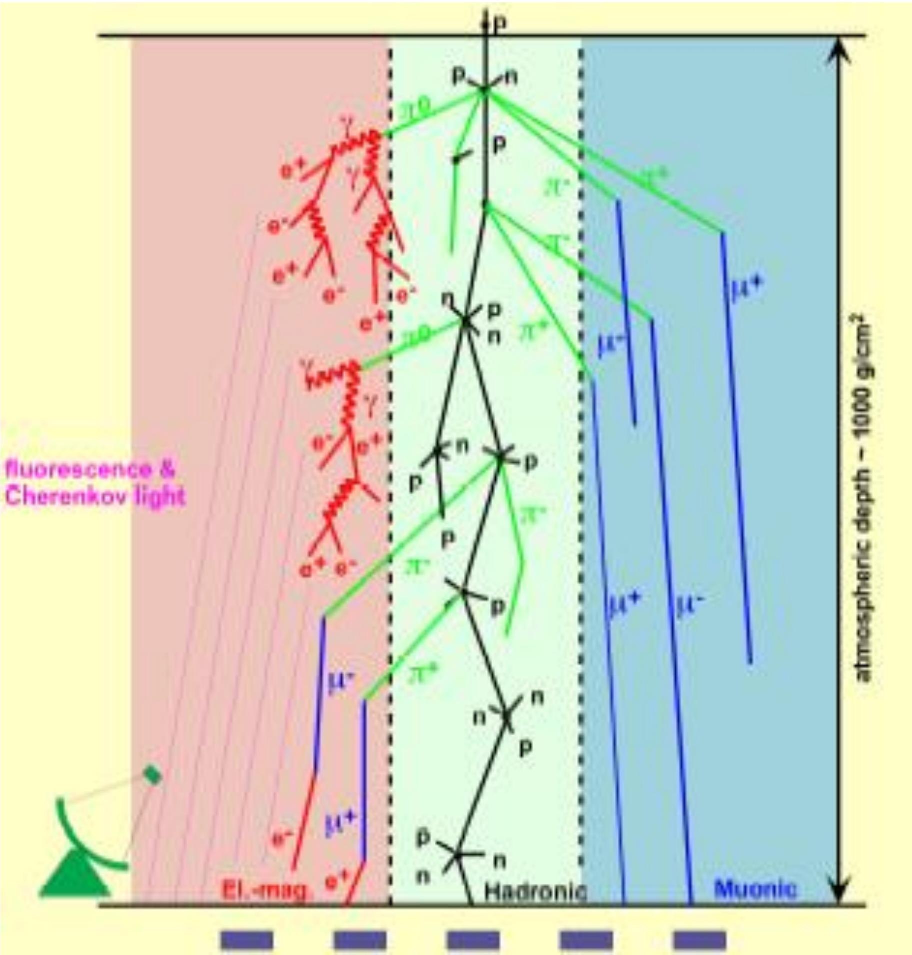
$$\mathrm{P(Fe)\ Air} \rightarrow \ \mathrm{Baryons} \quad (\text{leading, net-baryon} \neq 0)$$

$$\rightarrow \ \pi^0 \qquad (\ \pi^0 \rightarrow \ \gamma\gamma \rightarrow e^+e^- \ e^+e^- \rightarrow \ldots)$$

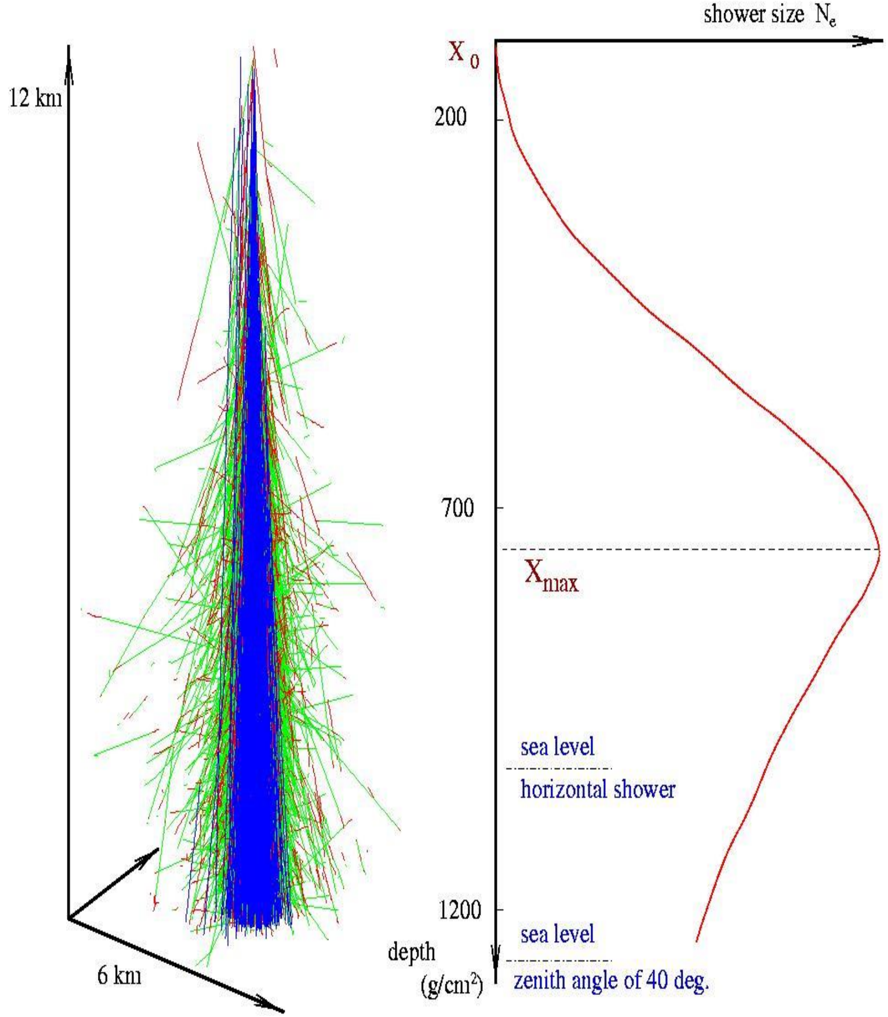
$$\rightarrow \ \pi^{\pm} \qquad (\pi^{\pm} \rightarrow \ \nu \ \mu^{\pm} \ \text{if} \ \ L_{decay} < \ L_{int})$$

$$\rightarrow \ K^{\pm}, \mathrm{D.} \ \ldots$$

Extensive Air Showers (EAS)



10^{19} eV



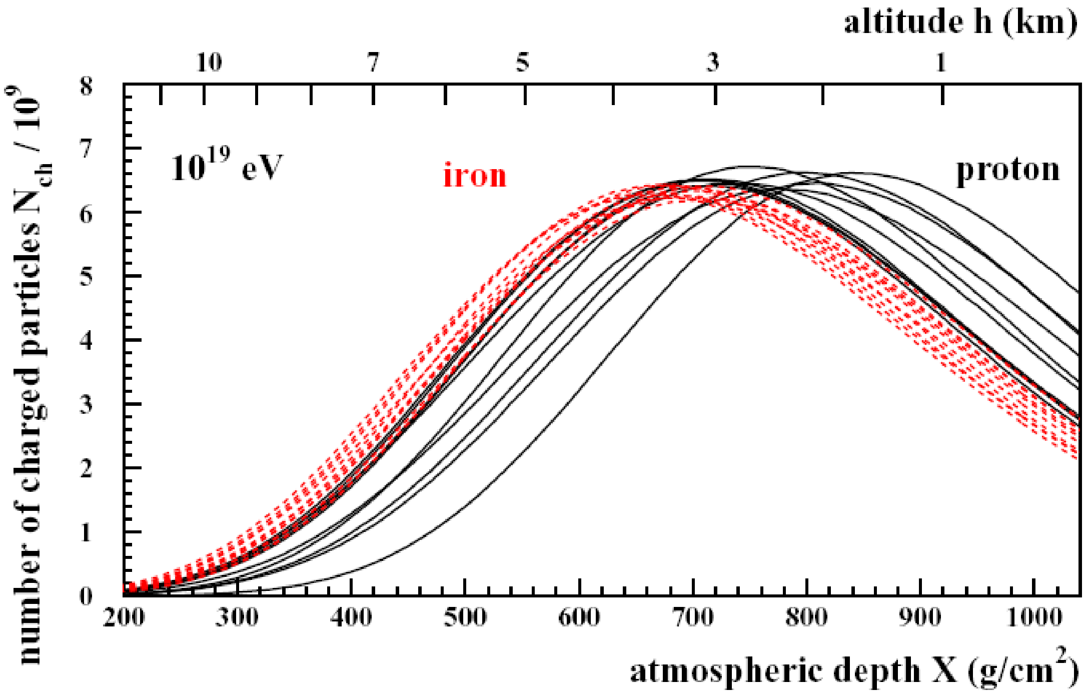
EAS longitudinal profiles

Gaisser

$$N_e = N_e^{\max}\left(\frac{X - X_1}{X_{\max} - \lambda}\right)^{\frac{X_{\max}-\lambda}{\lambda}} e^{-\left(\frac{X - X_1}{\lambda}\right)}$$

$N_e^{\max} \propto E$

$X_{\max} \propto \ln E$



Iron ~ 56 nucl(E/56)

Smaller fluctuactions

Smaller X_{max}

EAS transverse profiles

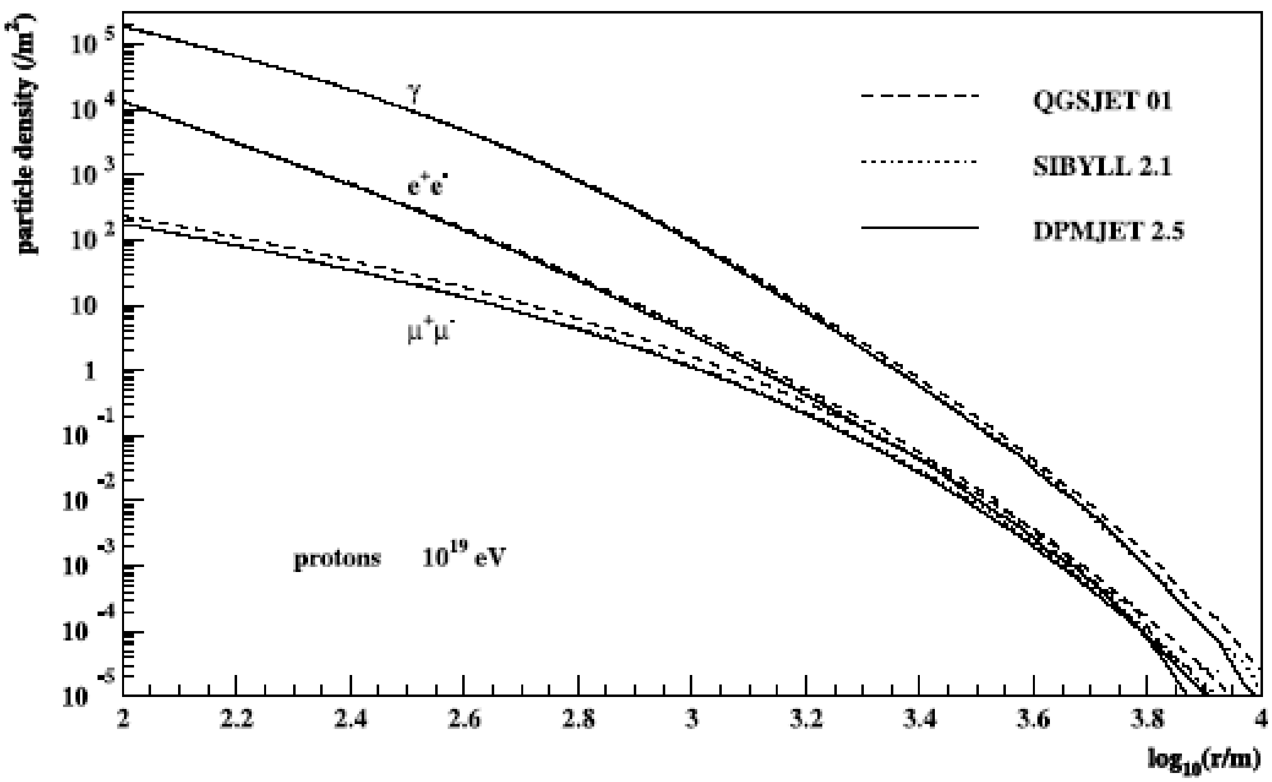
NKG (Nishimura, Kamata, Greisen)

$$\rho(r) = c(s) N_e / r_0^2 (r/r_0)^{s-2} (1 + r/r_0)^{s-4.5}$$

r_0: Moliére radius

s : shower age

J. Knapp et al. / Astroparticle Physics 19 (2003) 77–99



P_t distributions

Multiple Coulomb scattering

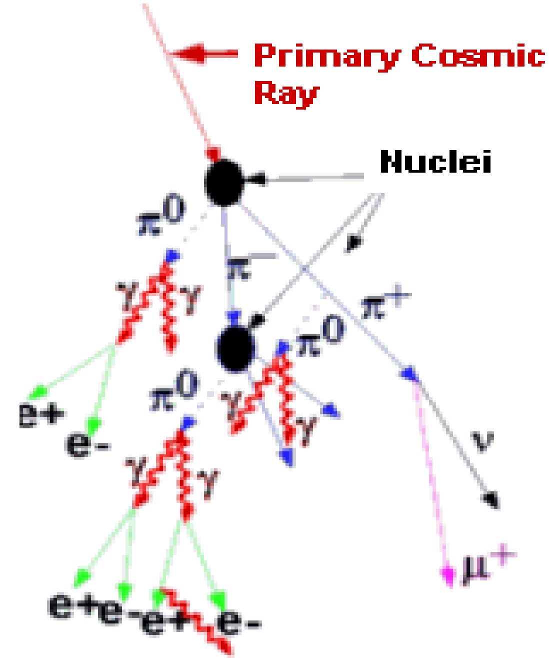
Shower development

P(Fe) Air $\rightarrow$ Baryons (leading, net-baryon $\neq$ 0)

$\rightarrow \pi^0$ ($\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^- e^+e^- \rightarrow \ldots$)

$\rightarrow \pi^\pm$ ($\pi^\pm \rightarrow \nu\, \mu^\pm$ if $L_{decay} < L_{int}$)

$\rightarrow K^\pm$, D. …



e.m. and weak interations

- well known !

hadronic interations

- large uncertainties !
- forward region, small p_t, very high $\sqrt{s}$
- main parameters: σ_{in}, k_{in}, <n>, (fraction π^0, Nb of Baryons, …)

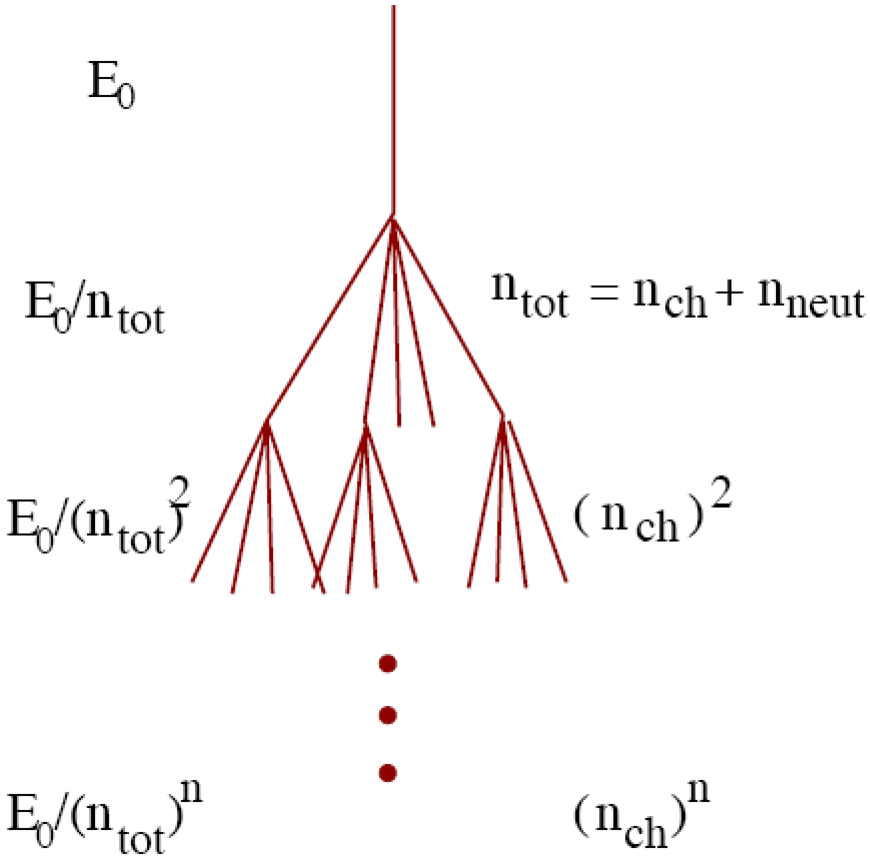
Nuclear fragmentation

- Nuclei are not just a superposition of nucleons !

Missing Energy

- 5% to 10% …

Muon production



Primary particle proton

π^0 decay immediately

$\pi^\pm$ initiate new cascades

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha$$

$$\alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

Assumptions:

- cascade stops at $E_{part} = E_{dec}$
- each hadron produces one muon

(Matthews, Astropart.Phys. 22, 2005)

Muon spectrum at Earth Surface

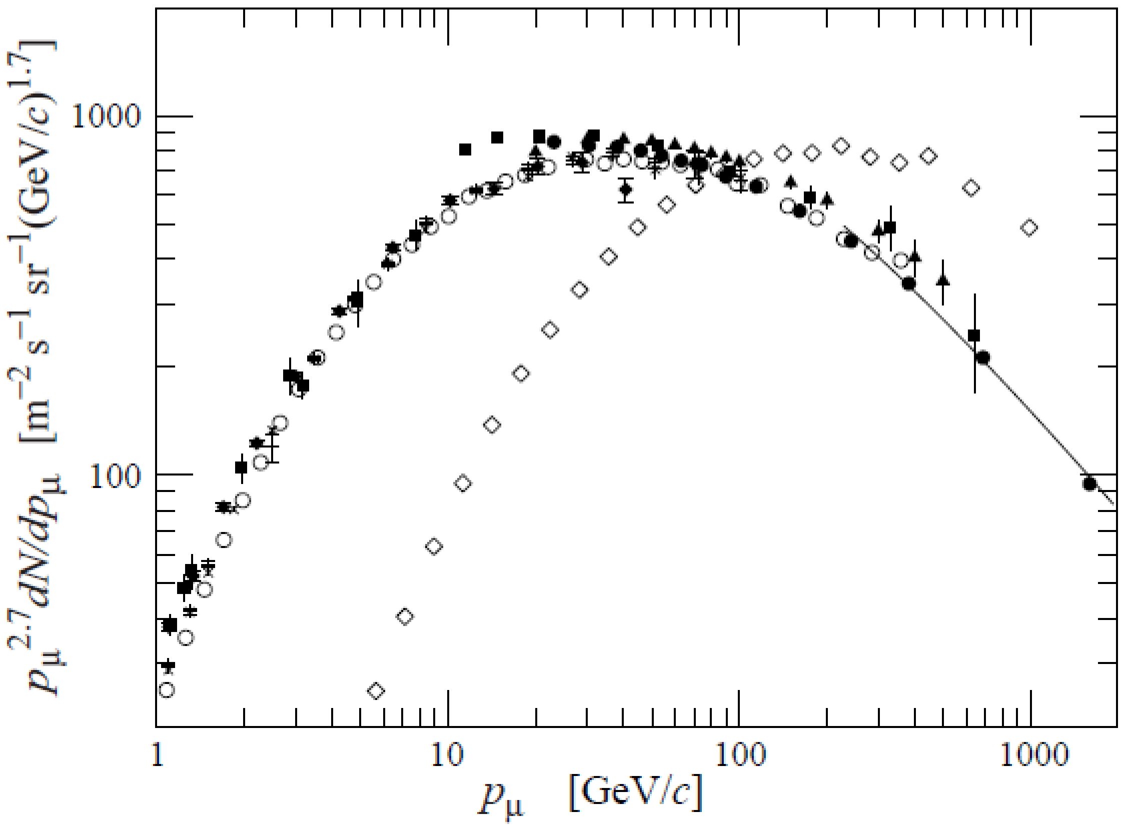


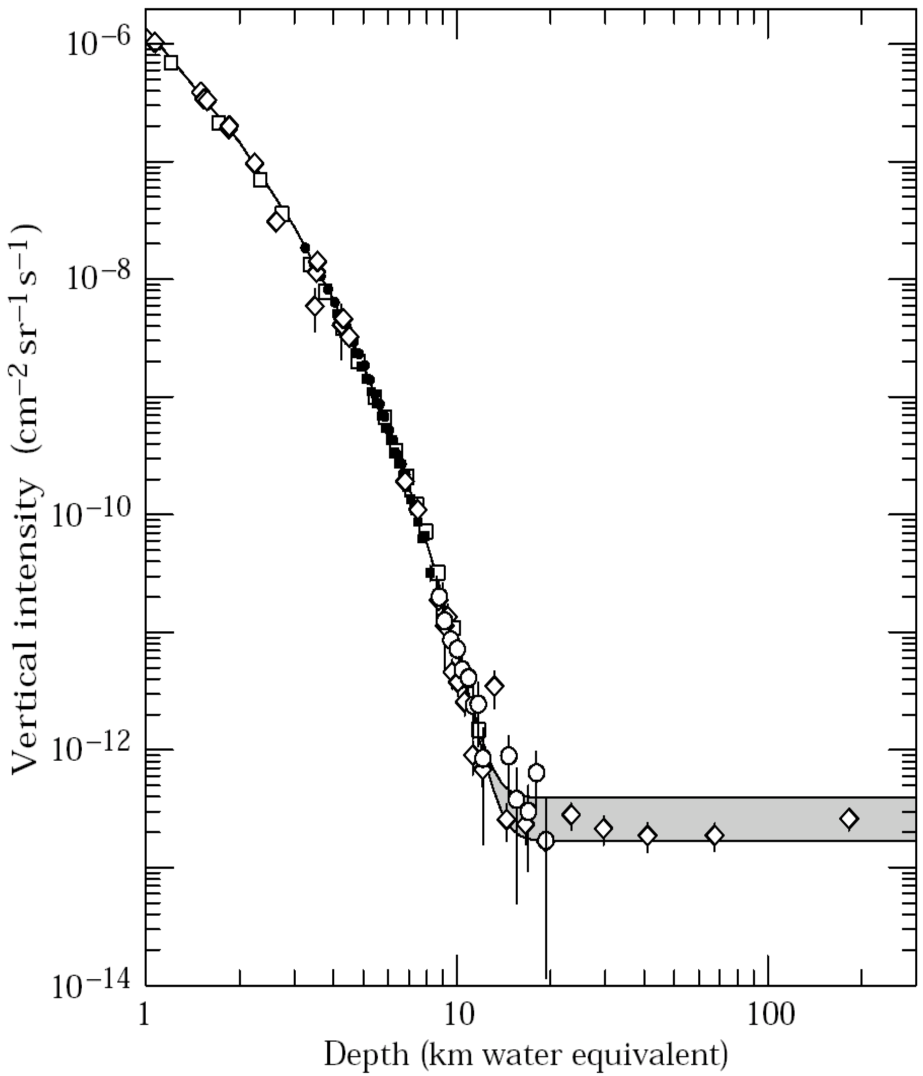
Figure 26.4: Spectrum of muons at $\theta = 0°$ (◆ [41], ■ [46], ▼ [47], ▲ [48], ×, + [43], ○ [44], and ● [45] and $\theta = 75°$ ◇ [49]) . The line plots the result from Eq. (26.4) for vertical showers. **J. Beringer et al (PDG) PR D86 010001 (2012)**

Under Earth

At the Earth surface :

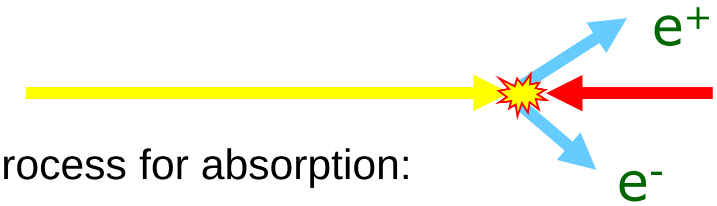
~70 m^{-2} s^{-1} sr^{-1}

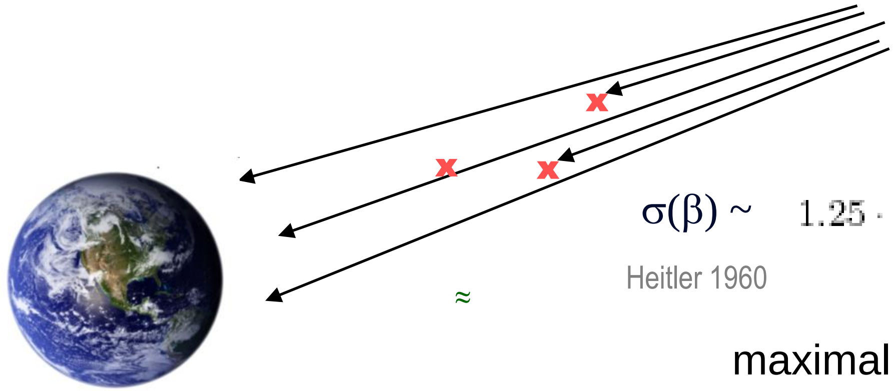
~1 cm^{-2} min^{-1} (Ω~π)



Place	Depth(KmWater)	Threshold(TeV)
Mt.Blanc	~ 5	~ 3
GranSasso	~ 3.5	~ 2
Kamiokande	~ 2.7	~ 1

Propagation of γ-rays





dominant process for absorption:

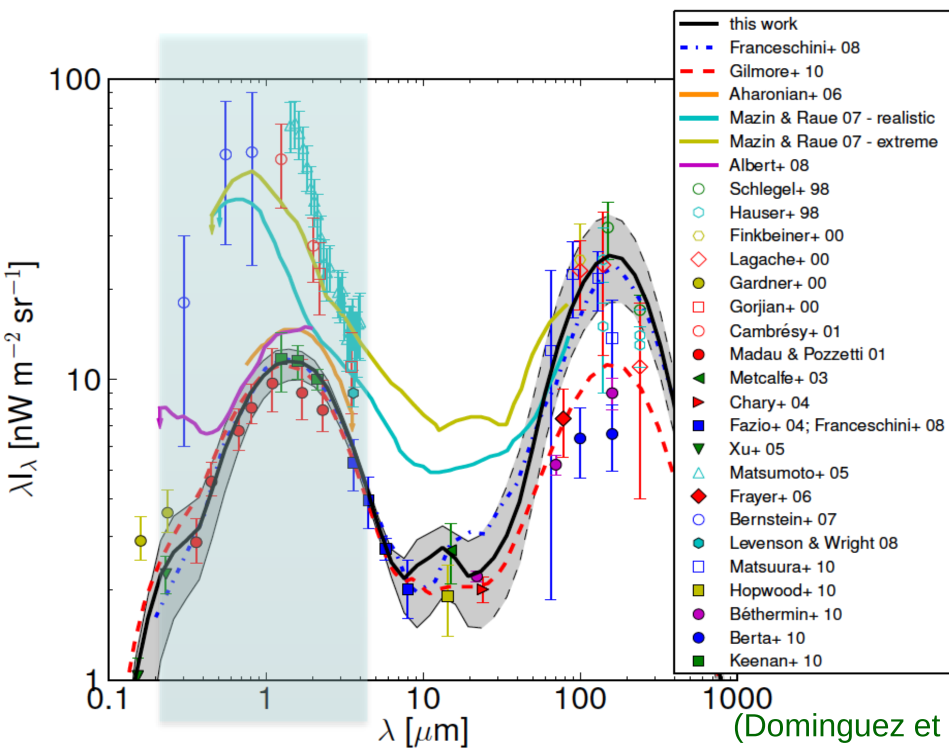
$$\gamma_{\text{VHE}}\gamma_{\text{bck}} \rightarrow e^{+}e^{-}$$

$$\sigma(\beta) \sim \quad 1.25 \cdot 10^{-25}(1-\beta^2)\cdot\left[2\beta(\beta^2-2)+(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]\,\text{cm}^2$$

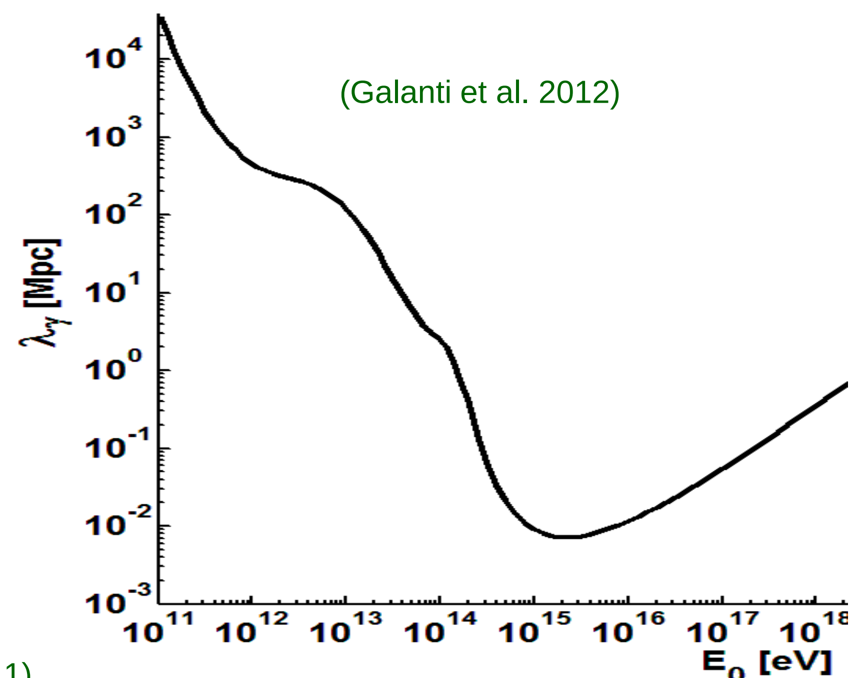
Heitler 1960

maximal for: $\boxed{\epsilon \simeq \frac{2m_e^2c^4}{E} \simeq \left(\frac{500\ \text{GeV}}{E}\right)\text{eV}}$

- For gamma rays, relevant background component is optical/infrared (EBL)
- different models for EBL: minimum density given by cosmology/star formation

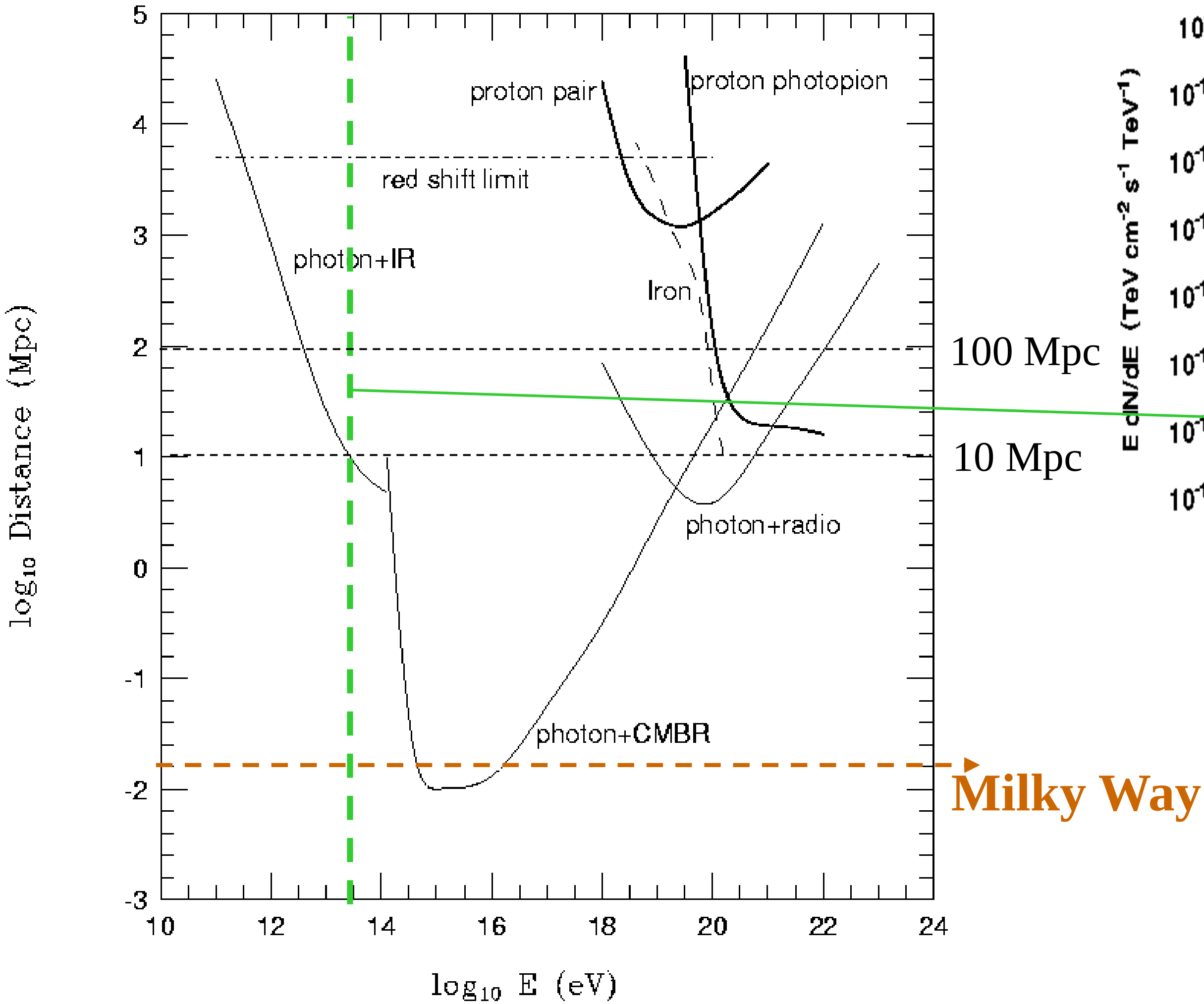


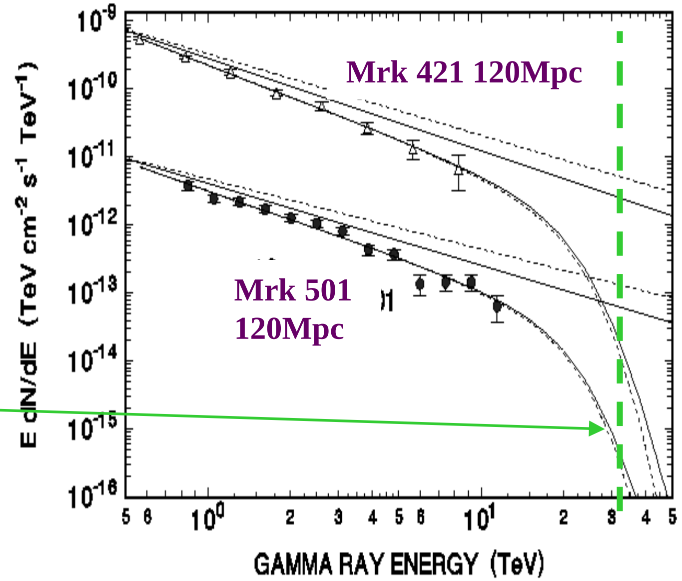
(Dominguez et al. 2011)



(Galanti et al. 2012)

The γ "GZK" $(\gamma\,\gamma \rightarrow e^+ e^-)$





Minimum at 10^{15} eV, but it recovers!

Extragalactic Sources

~50 Sources

…

1ES 1011+496 z=0.21 **MAGIC 2007**

1ES 0414+009 z=0.29 HESS/Fermi 2009

S5 0716+71 **z=0.31±0.08** **MAGIC 2009**

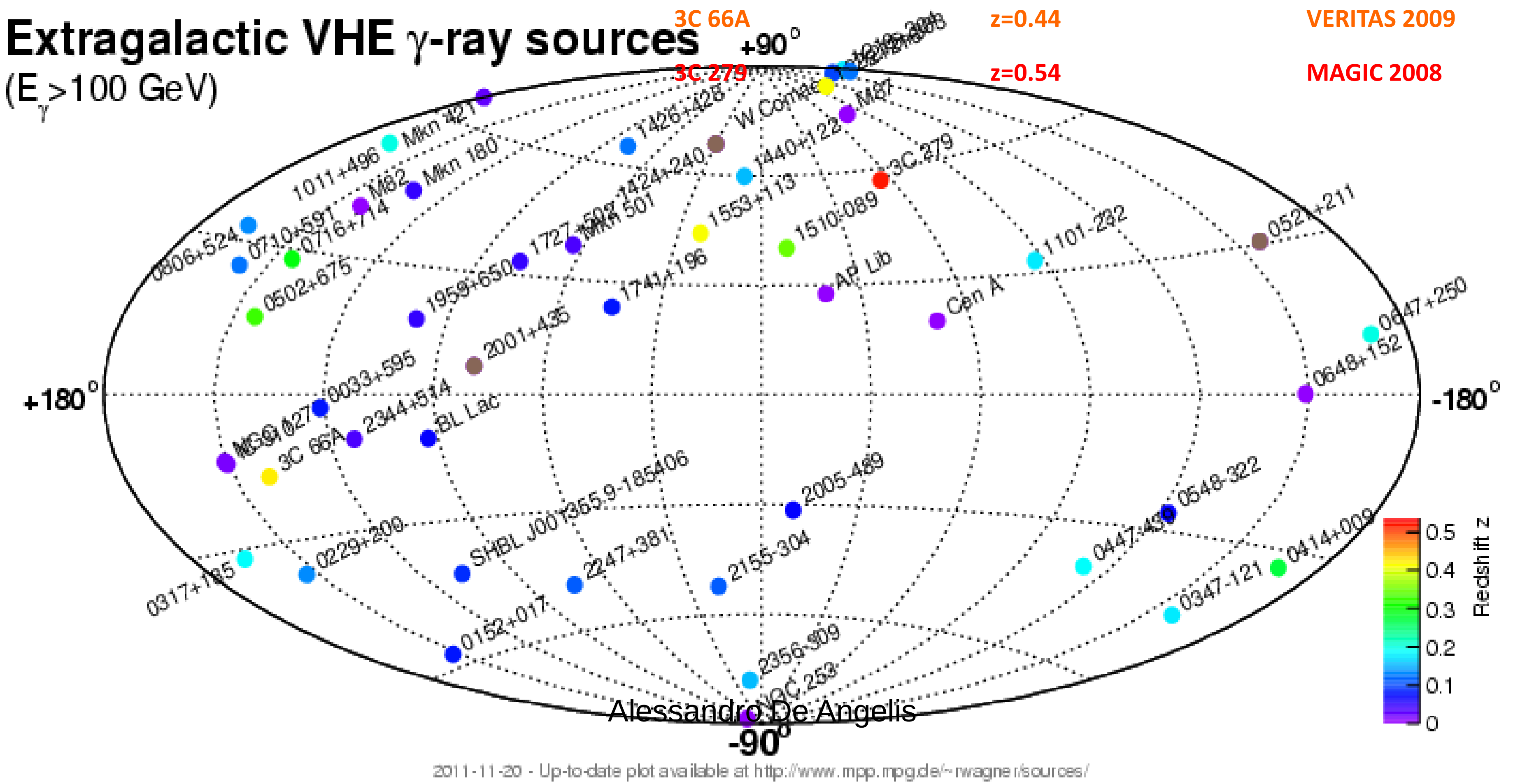
1ES 0502+675 z=0.34 VERITAS 2009

PKS 1510-089 z=0.36 HESS 2010

4C +21.43 **z=0.43** **MAGIC 2010**

3C 66A **z=0.44** **VERITAS 2009**

3C 279 **z=0.54** **MAGIC 2008**

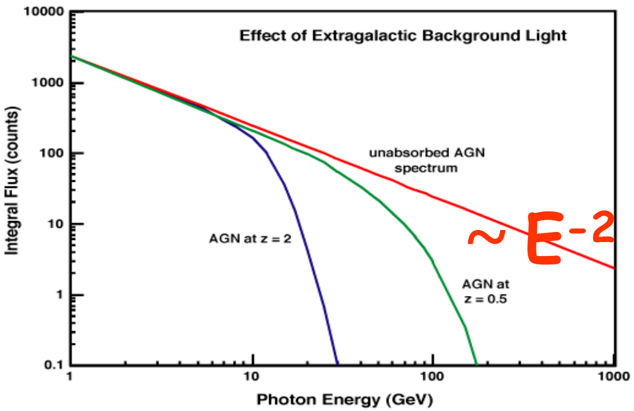


Are our AGN observations consistent with theory?

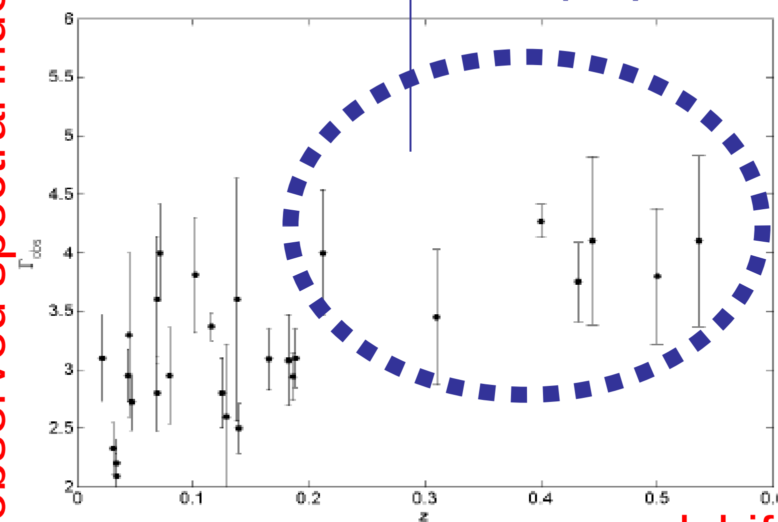
Selection bias?

New physics ?

Measured spectra affected by attenuation in the EBL :

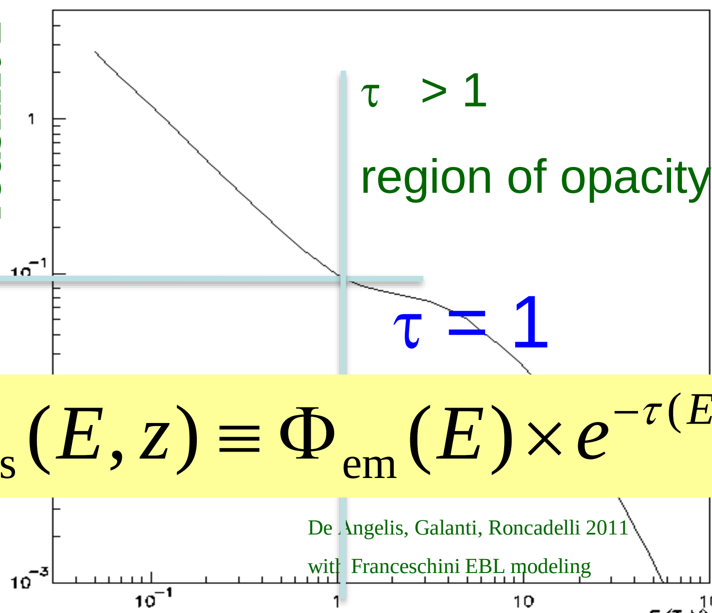


observed spectral index



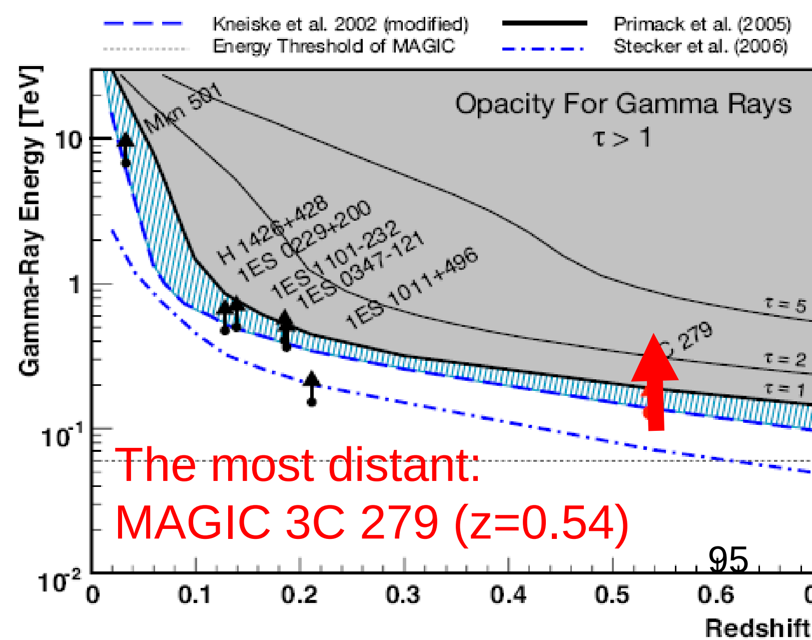
(DA, Galanti, Roncadelli; PRD 2011) redshift

redshift z



$$\Phi_{\text{obs}}(E,z) \equiv \Phi_{\text{em}}(E)\times e^{-\tau(E,z)}$$

γ ray energy (TeV)



The most distant:
MAGIC 3C 279 (z=0.54)

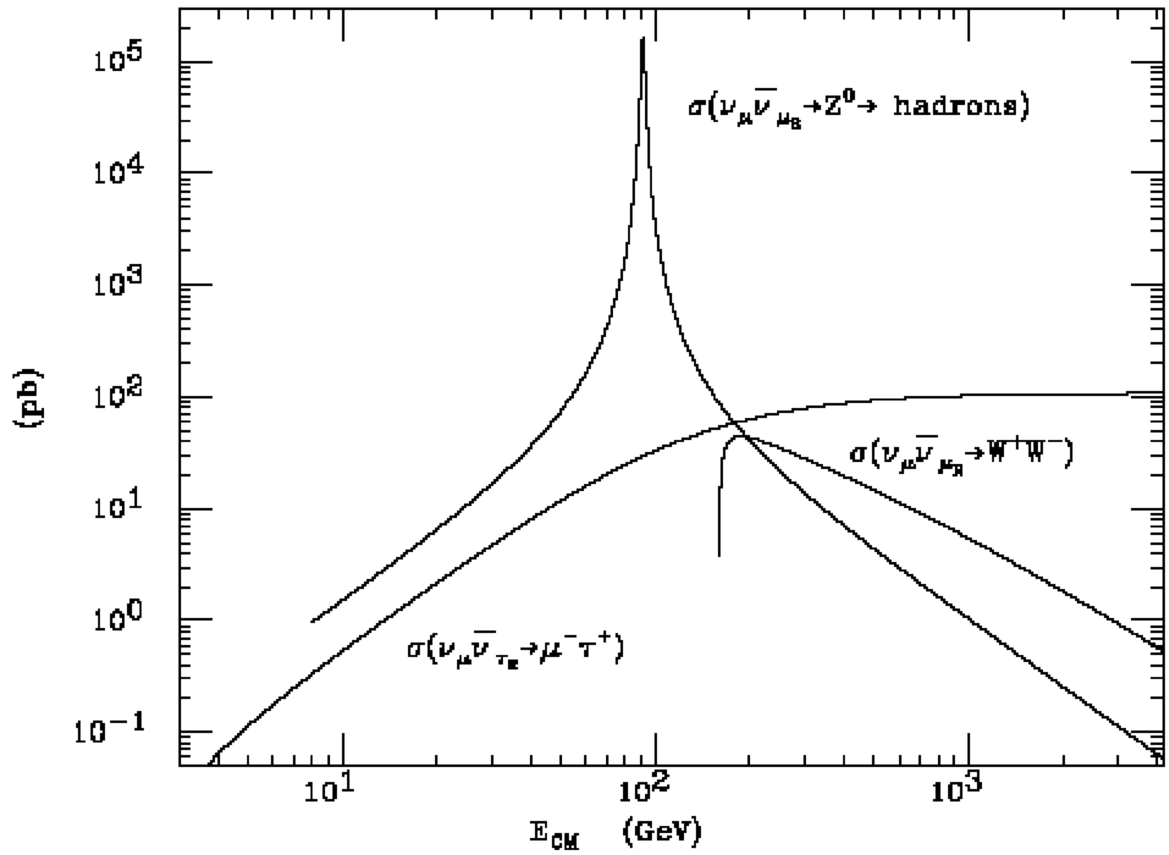
ν Propagation and the ν "GZK"

D.Fargion, B.Mele

ν $\nu_{rel} \rightarrow Z^0$

$\rightarrow W^+ W^-$

$\rightarrow Z^0 Z^0$



Neutrinos propagate unabsorbed and without deflection throughtout the universe up to $E_\nu \sim 10^{25}$ eV

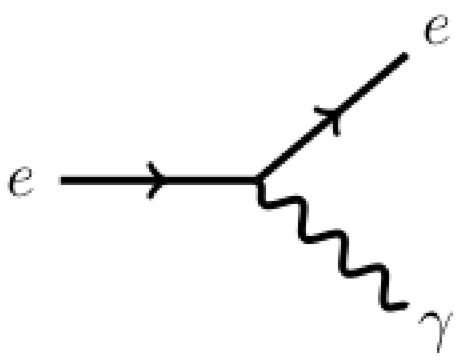
QED HE processes: bremsstrahlung for electrons…

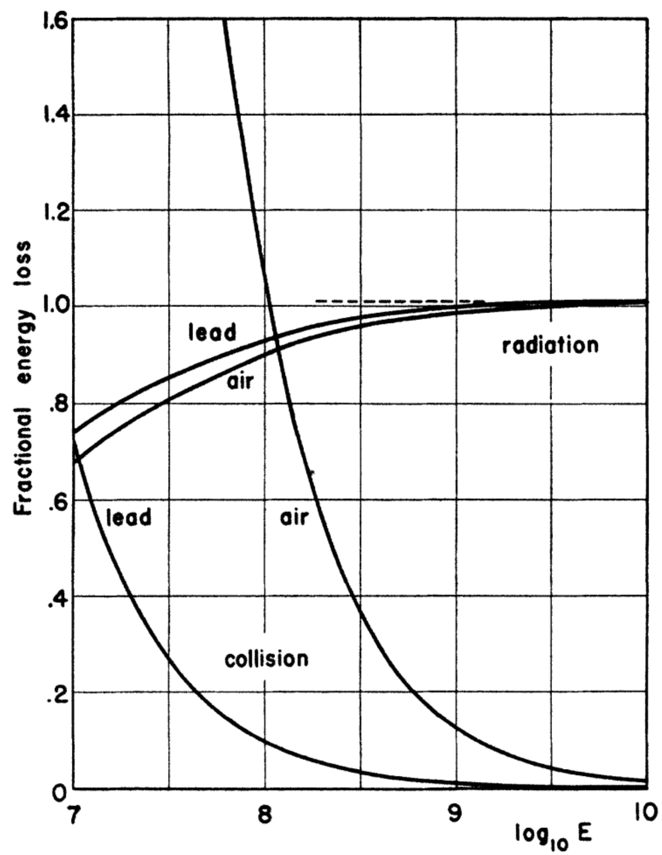
- (and pair production for photons). Forbidden in vacuo by 4-momentum conservation
  - Require interaction with the medium
- Bremsstrahlung (braking radiation): photons of momentum $q<E_e$ emitted with probability ~proportional to 1/q
  - (and collimated: ~ m_e/E)

  ie, energy emission is ~constant for each interval of photon energy; total is propto E
  - The dependence on the material appears through the radiation length Xo:

$$dE_e/dx = -1/X_o$$

  - Xo can be found in tables. It is ~300 m for air at NTP, ~43 cm for water; for density 1 g/cm^3 roughly proportional to A/Z^2
- Collision energy loss is almost constant (plateau)



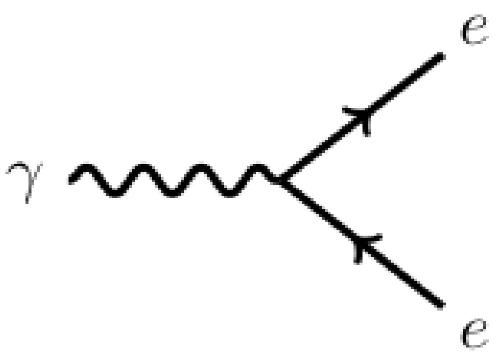


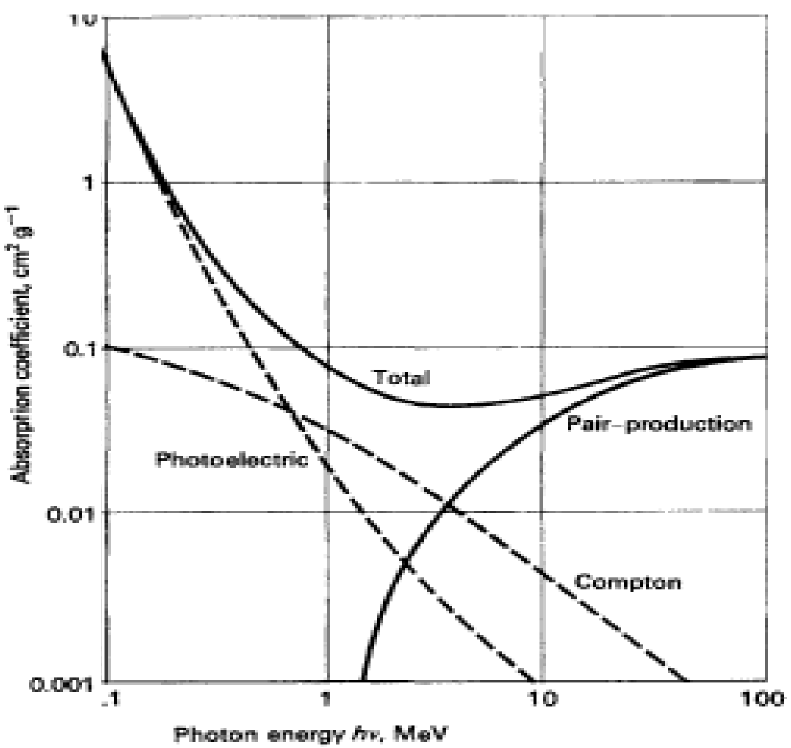
QED HE processes: …pair production for photons

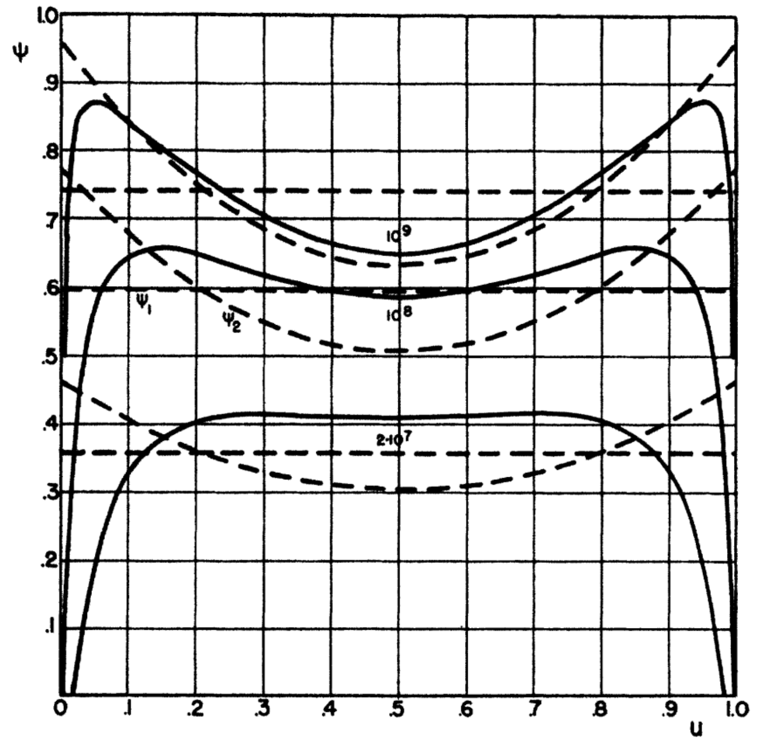
- Pair production:

  $\lambda = (9/7)\ Xo$ for $E\gamma >> 2m_e$

  Energy spectrum ~ flat





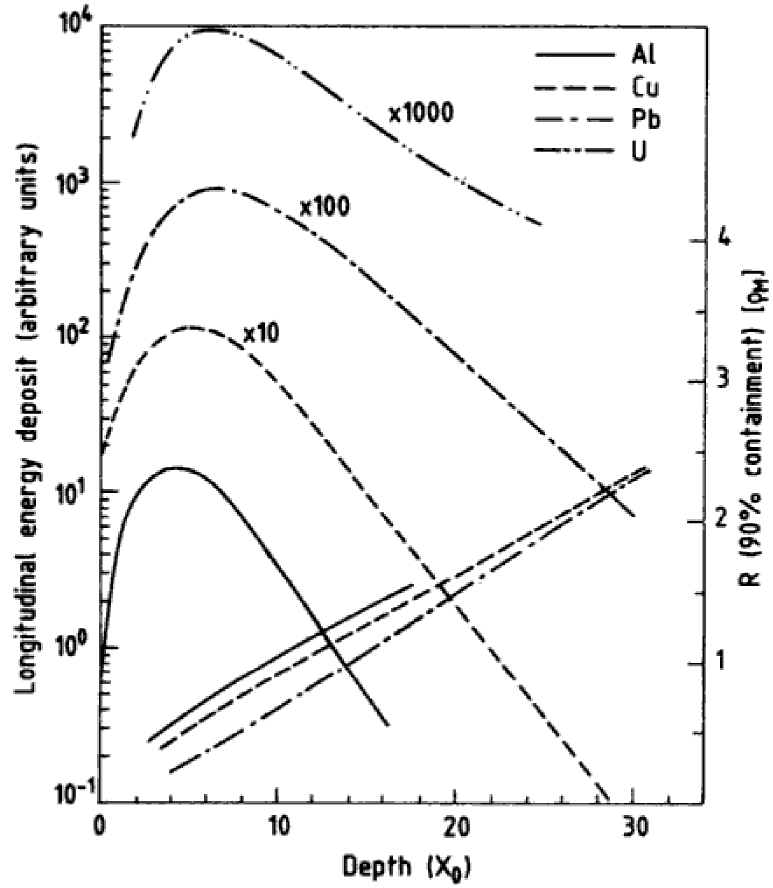


Electromagnetic showers

- When a high-energy e or γ enters an absorber, it initiates an em cascade as pair production and bremsstrahlung generate more e and γ with lower energy
- The ionization loss becomes dominant < a critical energy E_c
  - E_c ~ 84 MeV in air, ~73 MeV in water; ~ (550/Z)MeV
    - Approximate scaling in $y = E/E_c$
  - The longitudinal development ~scales as the radiation length in the material: $t = x/Xo$
  - The transverse development scales approximately with the Moliere radius $R_M \sim (21\ \mathrm{MeV}/E_c)\ Xo$
    - In average, only 10% of energy outside a cylinder w/ radius R_M
    - In air, R_M ~ 80 m; in water R_M ~ 9 cm
- Electrons/positrons lose energy by ionization during the cascade process
- Not a simple sequence: needs Monte Carlo calculations

An analytic model: Rossi's "approximation B"

- Rossi in 1941 published an analytical formulation for the shower development as a set of 2 integro-differential equations under the approximation that:
  - Electrons lose energy by ionization & bremsstrahlung; asymptotic formulae hold
  - Photons undergo pair production only; asymptotic formulae hold ($E > 2\ m_e$)
- Very good approximation until $E \sim E_c$

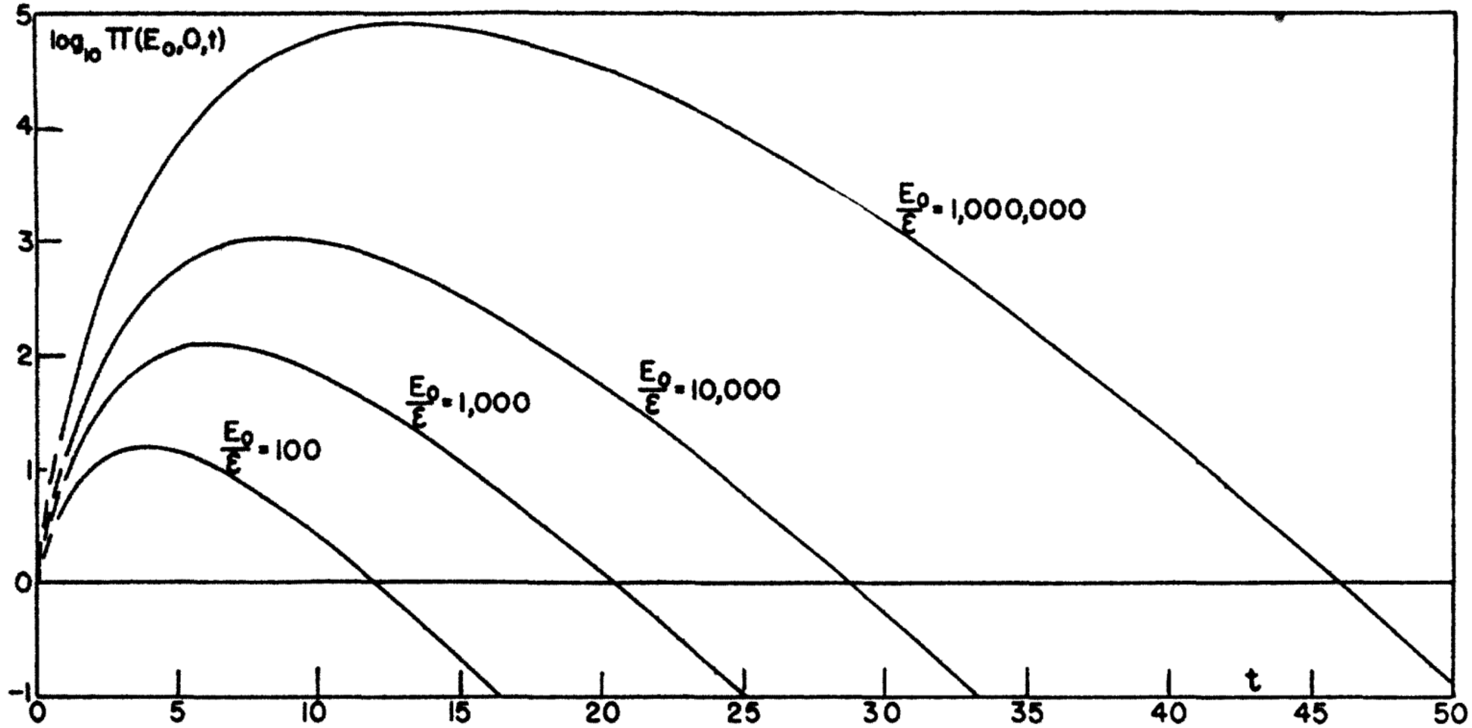


	Incident electron	Incident photons
Peak of shower, t_{max}	$1.0 \times (\ln y - 1)$	$1.0 \times (\ln y - 0.5)$
Centre of gravity, t_{med}	$t_{max} + 1.4$	$t_{max} + 1.7$
Number e^+ and e^- at peak	$0.3\,y \times (\ln y - 0.37)^{-1/2}$	$0.3\,y \times (\ln y - 0.31)^{-1/2}$
Total track length T	y	y

A snapshot of Rossi's equations (you can solve them, but…)

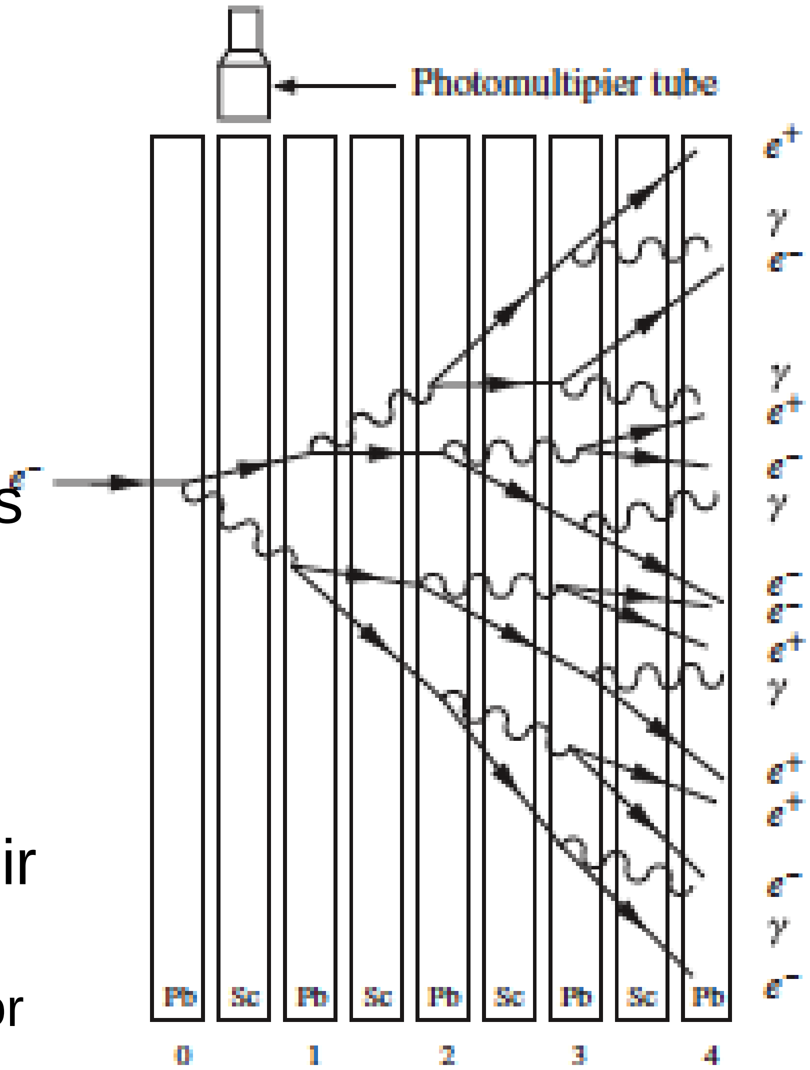
$$\frac{\partial \pi(E,t)}{\partial t} = 2\int_0^1 \gamma\left(\frac{E}{u},t\right)\psi_0(u)\frac{du}{u} - \int_0^1 \left[\pi(E,t) - \frac{1}{1-v}\pi\left(\frac{E}{1-v},t\right)\right]\varphi_0(v)dv + \epsilon\frac{\partial \pi(E,t)}{\partial E}$$

$$\frac{\partial \gamma(W,t)}{\partial t} = \int_0^1 \pi\left(\frac{W}{v},t\right)\varphi_0(v)\frac{dv}{v} - \sigma_0\gamma(W,t)$$



A simplified approach (Heitler)

- Qualitative features may be obtained from a simple model
  1. Each electron with $E>E_C$ travels 1 Xo and then gives up half of its energy to a bremsstrahlung photon
  2. Each photon with $E>E_C$ travels 1 Xo and then creates an e+e- pair with each particle taking E/2
  3. Electrons with $E<E_C$ cease to radiate and lose the rest of their energy by collisions
     - Ionization losses are negligible for $E>E_C$



Results from the simplified approach

- If the initial electron has energy $E_0 >> E_C$, after t Xo the shower will contain 2^t particles. ~equal numbers of e+, e-, γ, each with an average energy

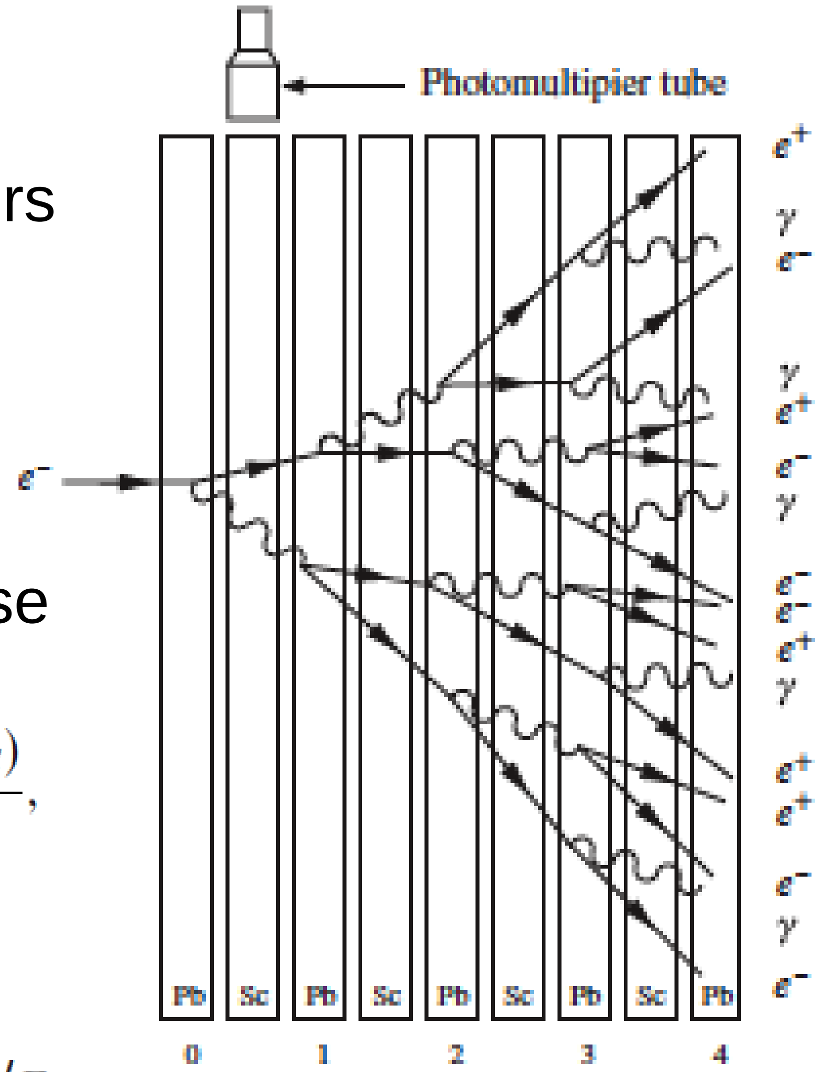
$$E(t) = E_0/2^t$$

- The multiplication process will cease when $E(t)=E_C$

$$t_{max} = t\,(E_C) \equiv \frac{\ln\,(E_0/E_C)}{\ln 2},$$

and the number of particles at this point will be

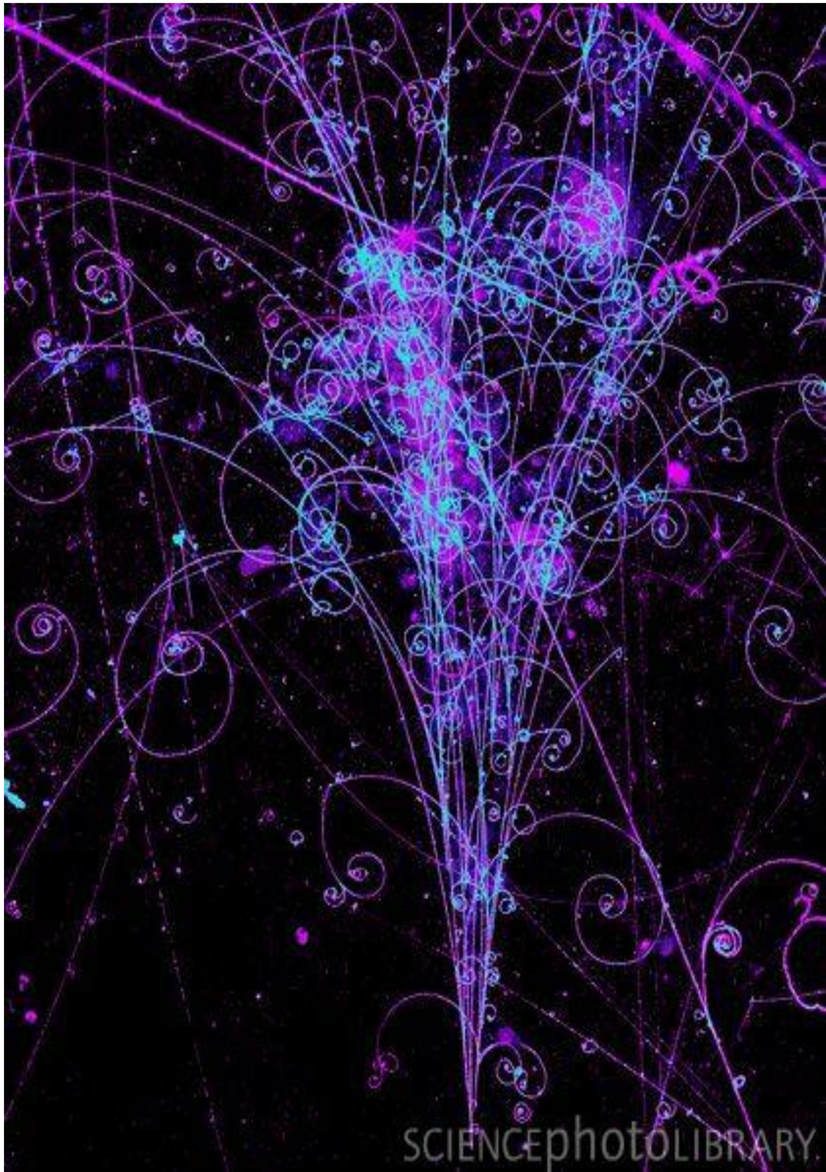
$$N_{max} = \exp\,(t_{max}\,\ln\,2) = E_0 \big/ E_C$$



Energy measurement

– Errors asymptotically dominated by statistical fluctuations:

$$\frac{\sigma_E}{E} \cong \frac{k_E}{\sqrt{E}} \oplus c$$



Hadronic showers

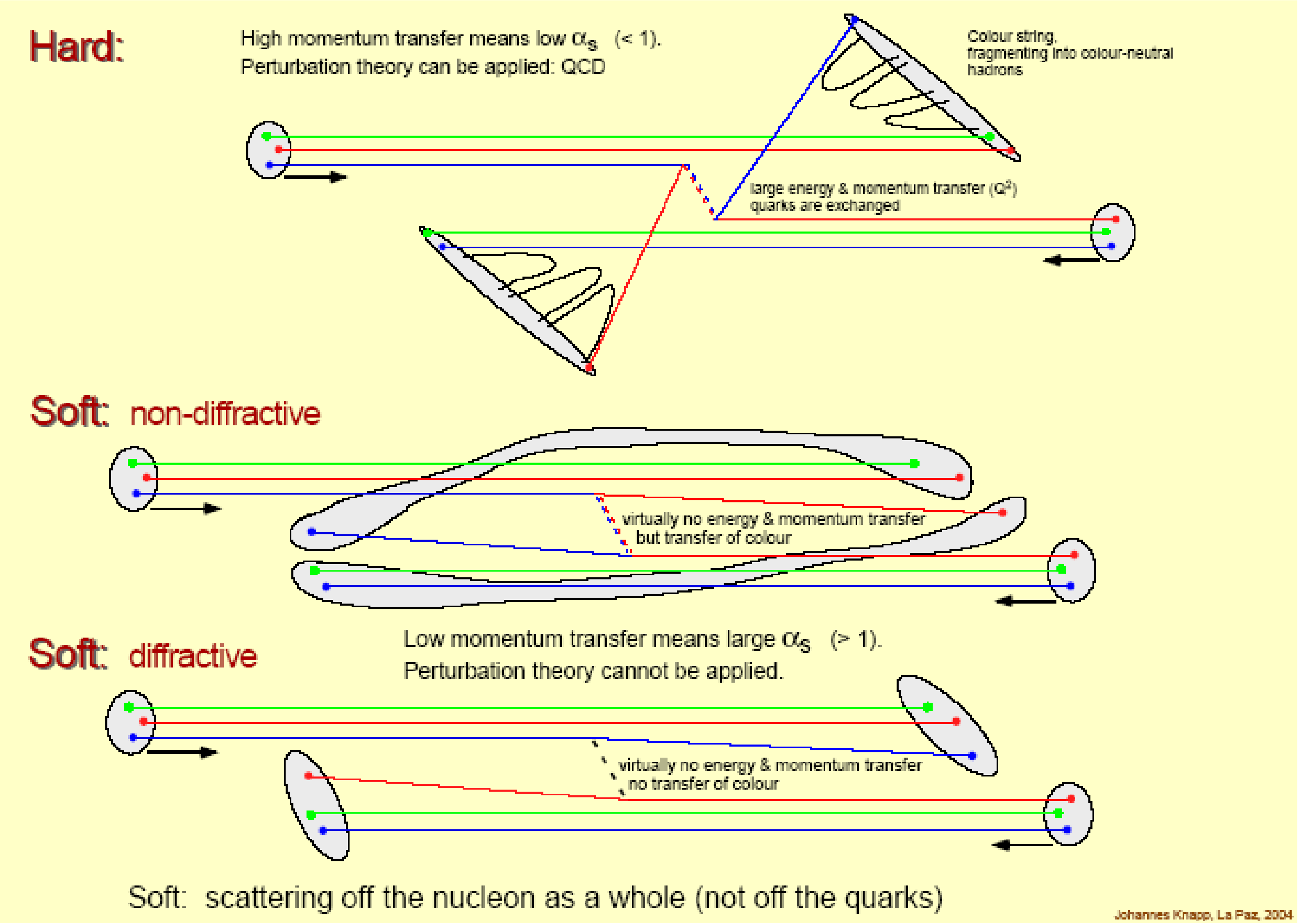
- Although hadronic showers are qualitatively similar to em, shower development is more complex because many different processes contribute
  - Larger fluctuations
- Some of the contributions to the total absorption may not give rise to an observable signal in the detector
  - Examples: nuclear excitation and leakage of secondary muons and neutrinos
- Depending on the proportion of π^0s produced in the early stages of the cascade, the shower may develop predominantly as an electromagnetic one because of the decay $\pi^0 \rightarrow \gamma\ \gamma$
- The scale of the shower is determined by the nuclear absorption length λ_H
  - Typically $\lambda_H > Xo$

Hard and soft hadronic interactions

J. Knapp

Perturbative QCD

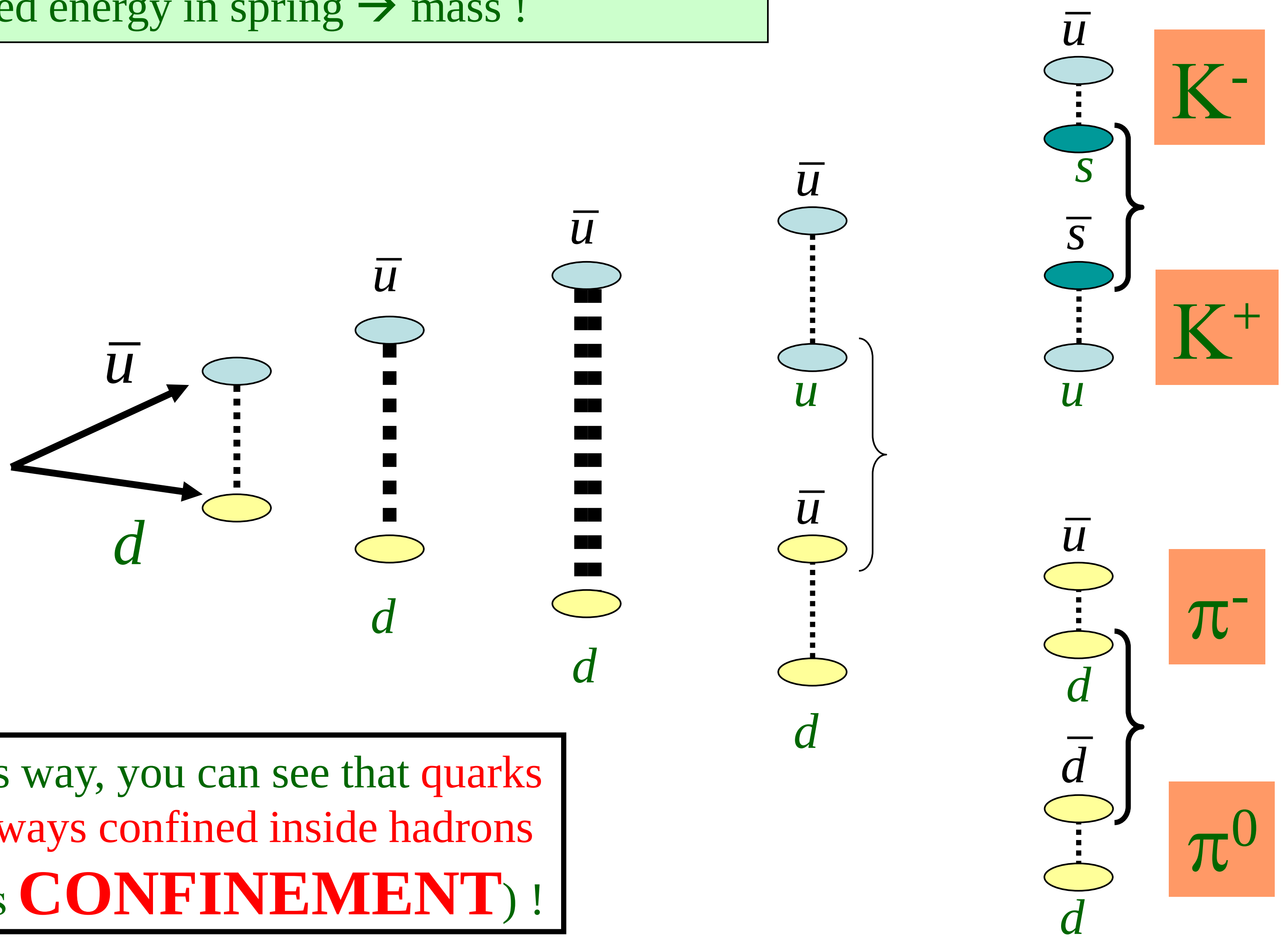
Pomeron exchange GRT



String fragmentation

Think of the gluons being exchanged as a spring… which if stretched too far, will snap! Stored energy in spring → mass !

Hadrons!



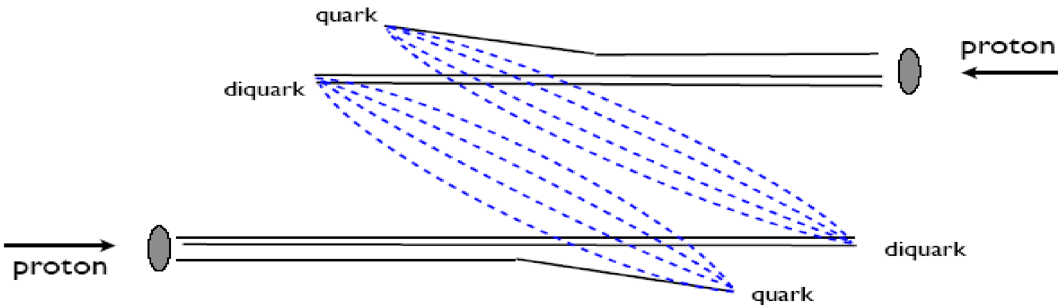
In this way, you can see that quarks are always confined inside hadrons (that's **CONFINEMENT**) !

“Standard” Hadronic models (low pt)

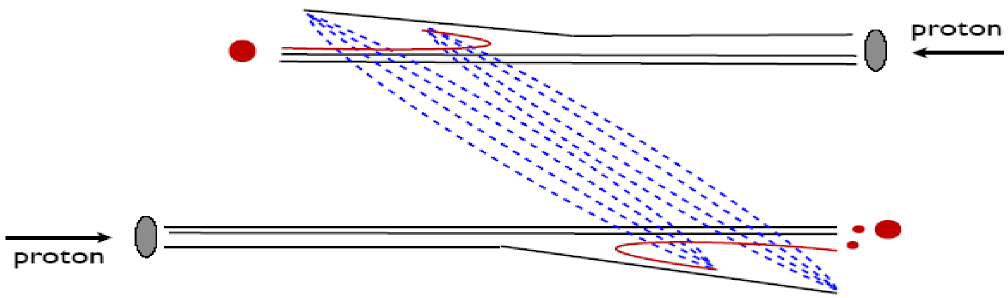
Minimum string configuration

Ralph Engel

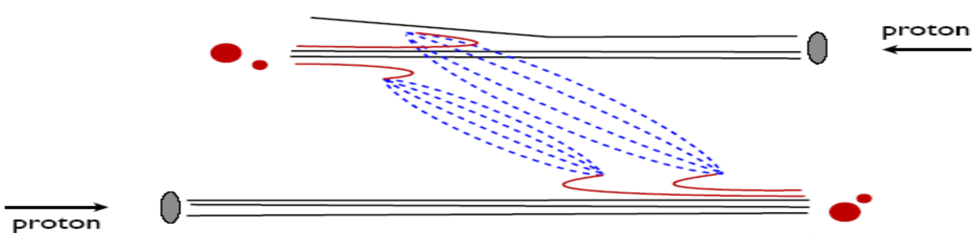
SIBYLL



QGSJET



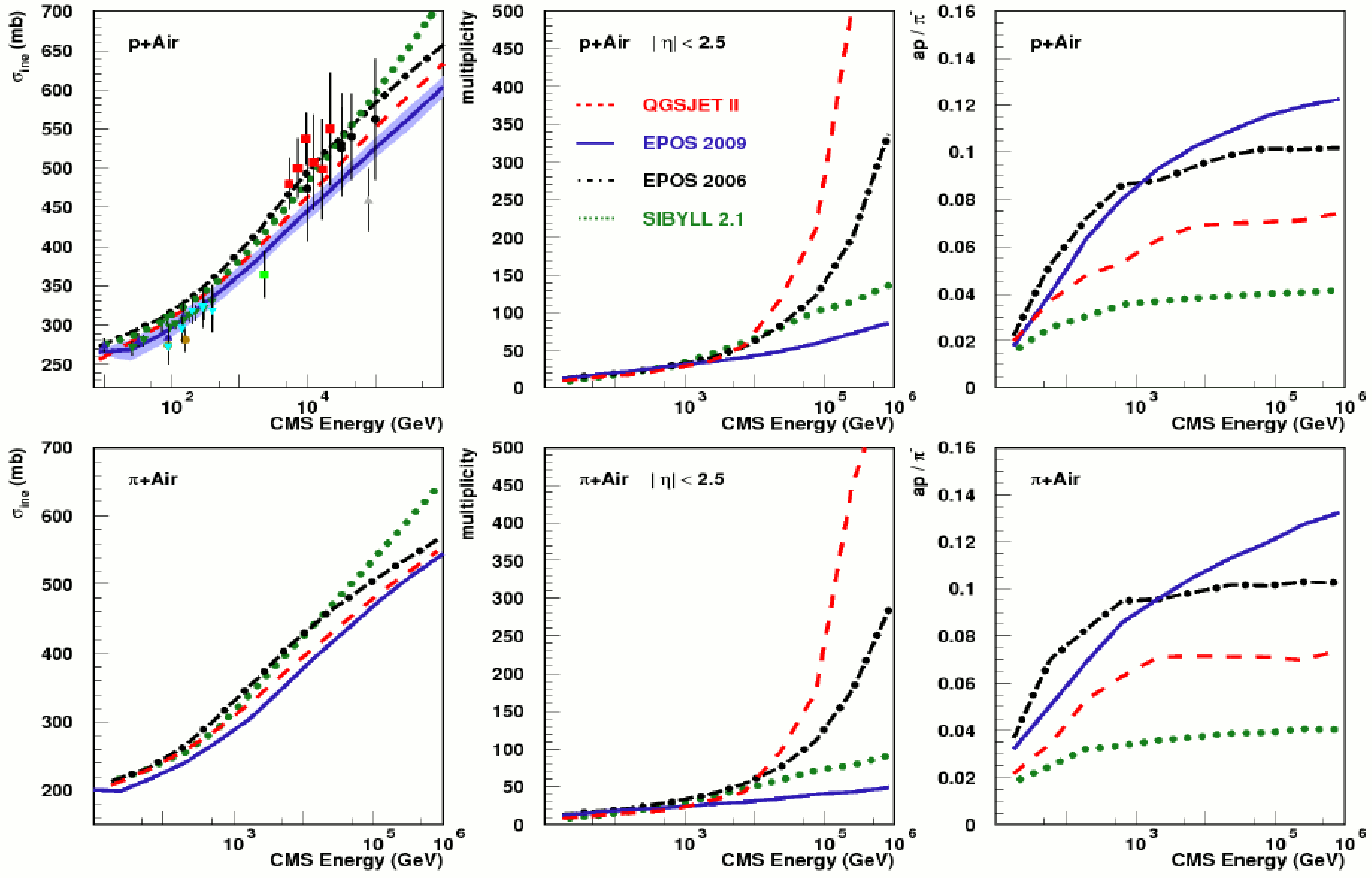
EPOS



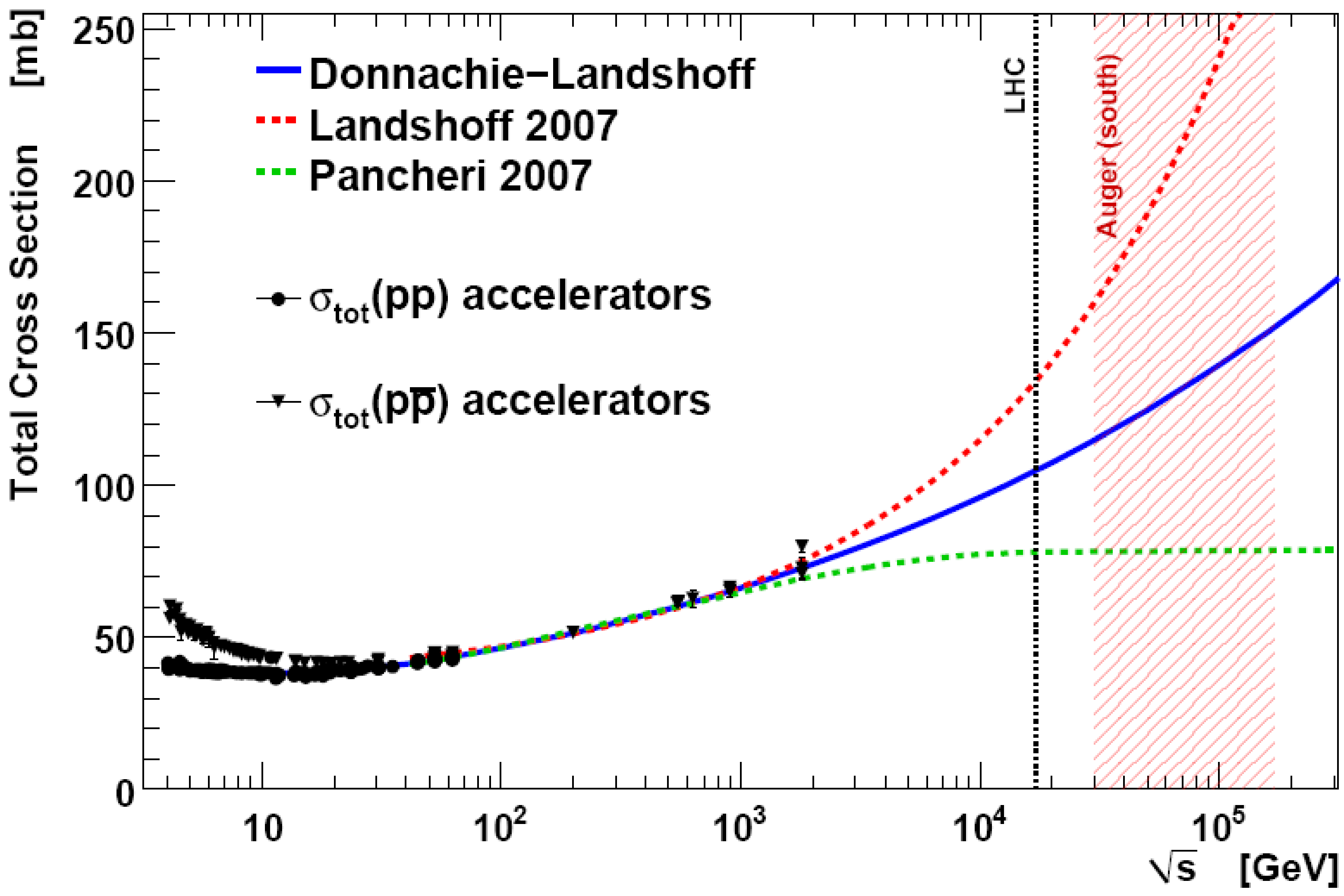
Hadronic model parameters

P.Tanguy

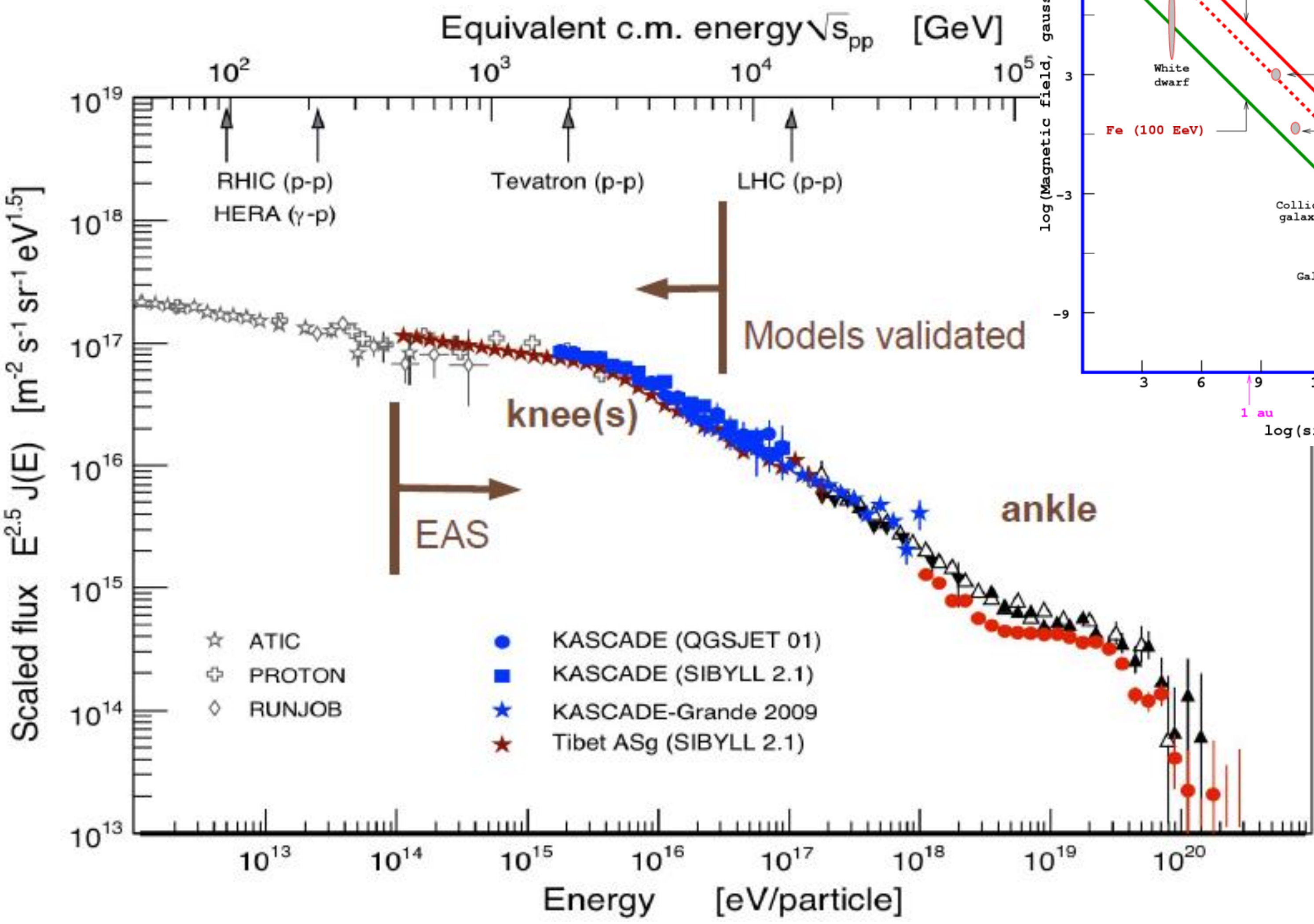
p air

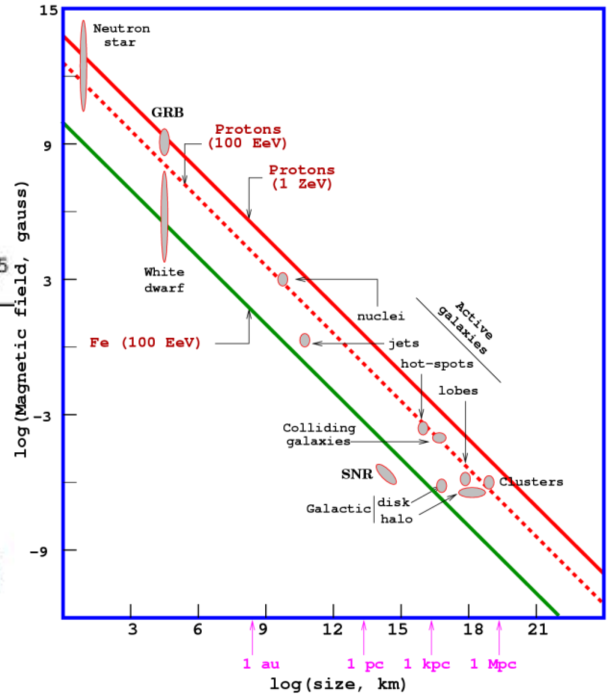


Cross sections extrapolations …



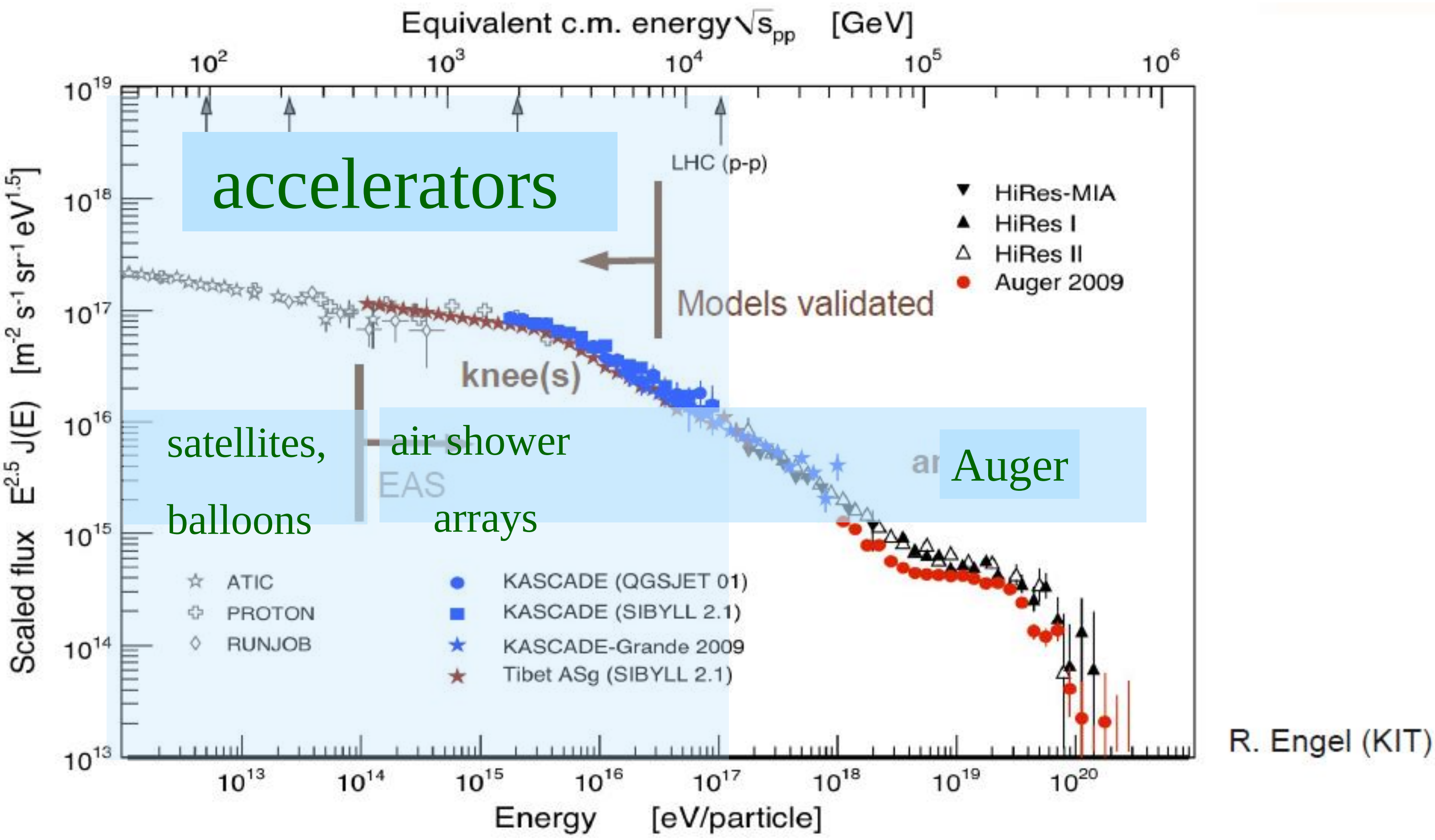
Cosmic Rays





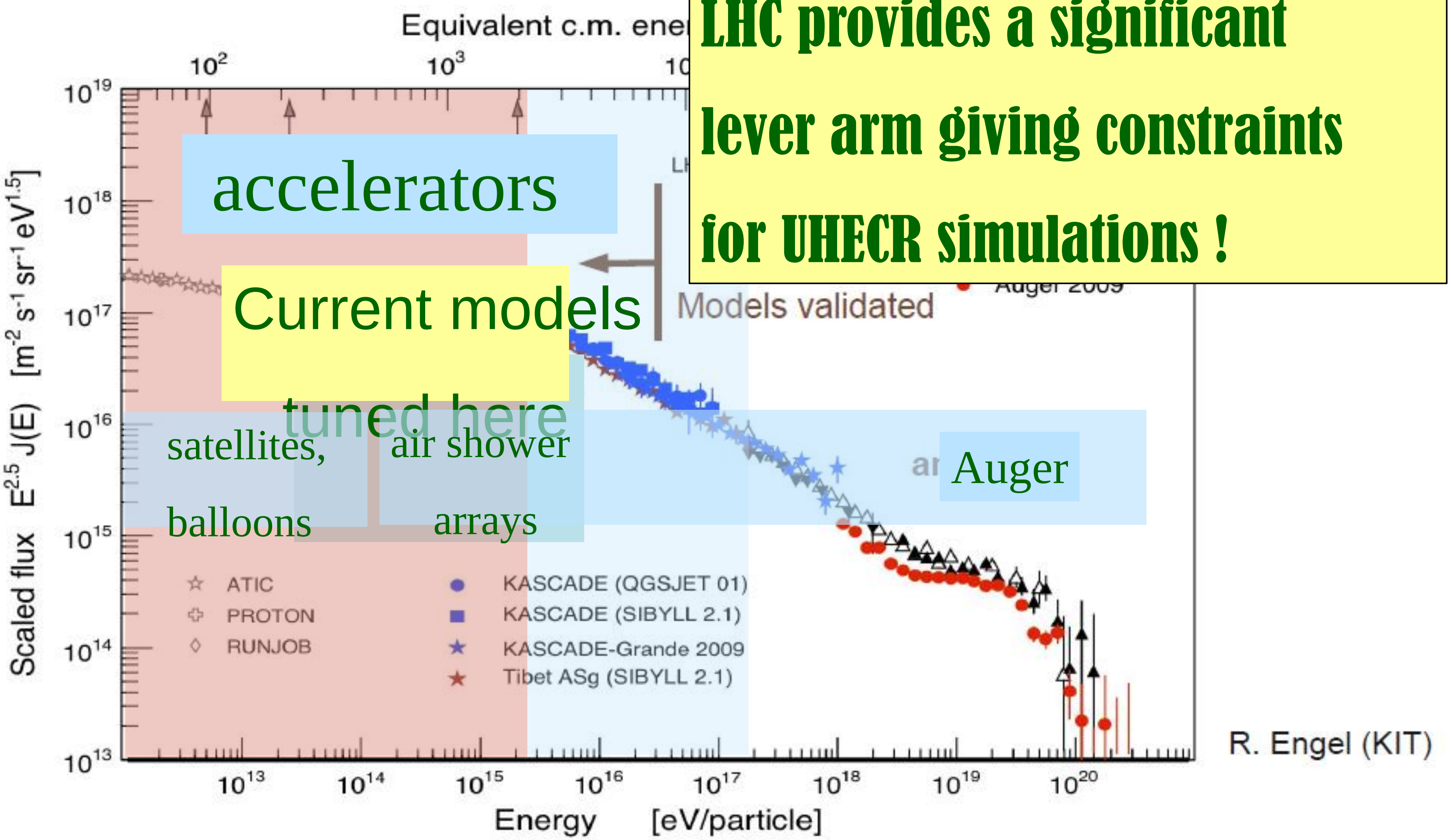
R. Engel (KIT)

Cosmic Rays and LHC

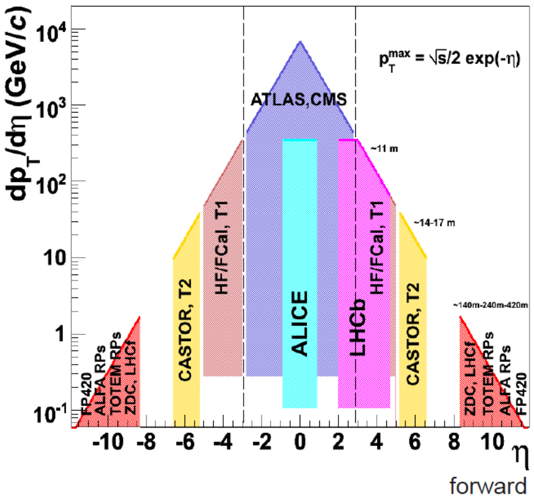


Cosmic Rays and LHC

LHC provides a significant lever arm giving constraints for UHECR simulations !

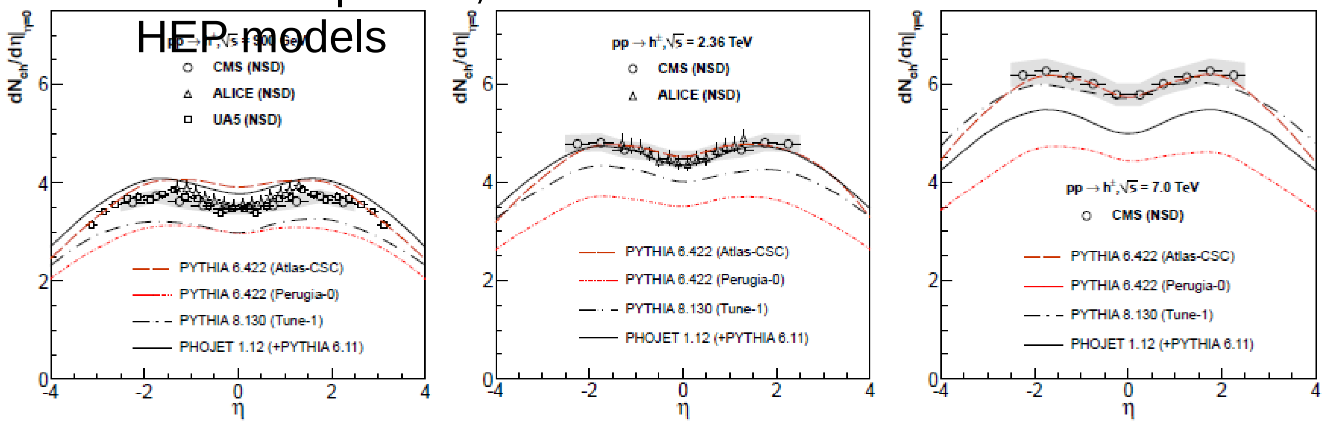


Small-x region (LHC as a pathfinder for CR, and vice-versa)

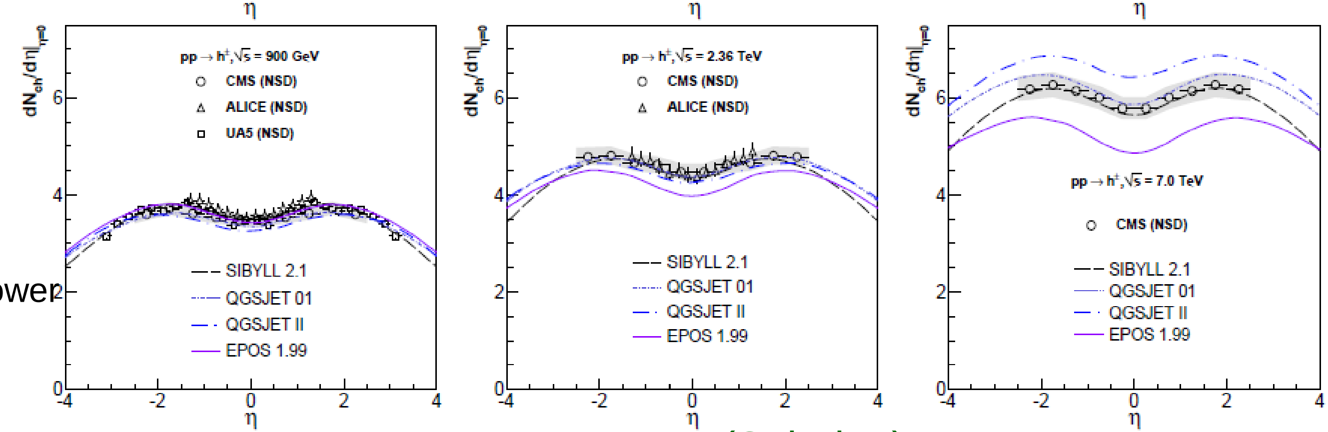


- LHC detectors cover all wide rapidity range
  - EAS models bracket accelerator data
  - no model perfect, but EAS models seem to do better than HEP models

- **HEP**
  High Energy Physics
  models



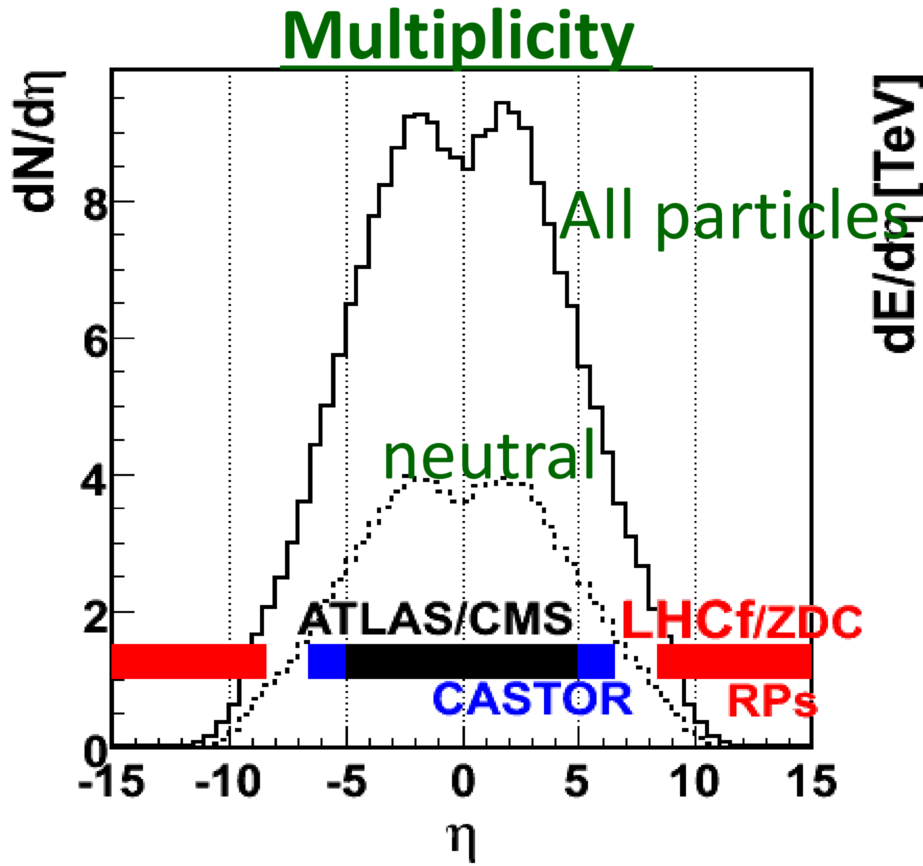
- **EAS**
  Extensive Air Shower
  models

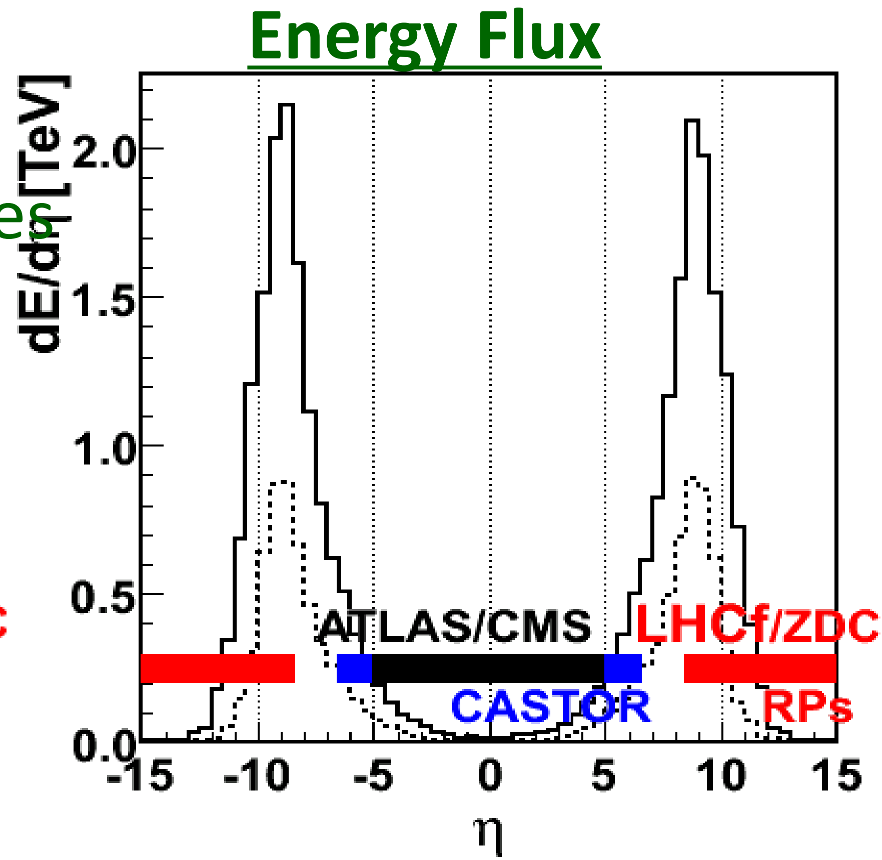


(Spiering)

LHC Kinematics (14 TeV)

Takashi SAKO



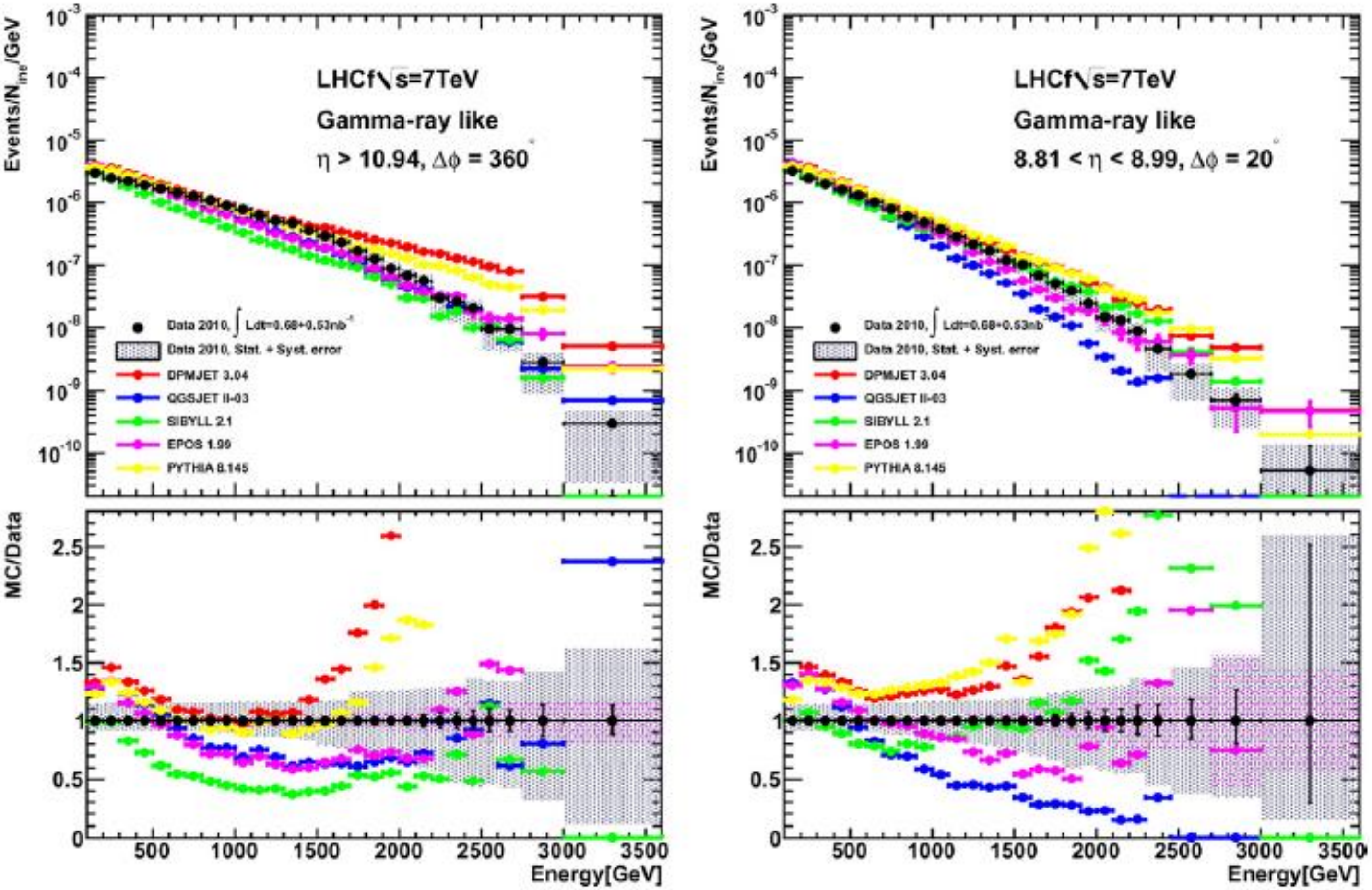


pseudo-rapidity; $\eta = -\ln(\tan(\theta/2))$

Most of the energy flows into very forward region

LHCf: forward photon production

Forward production of gamma-rays with low pt



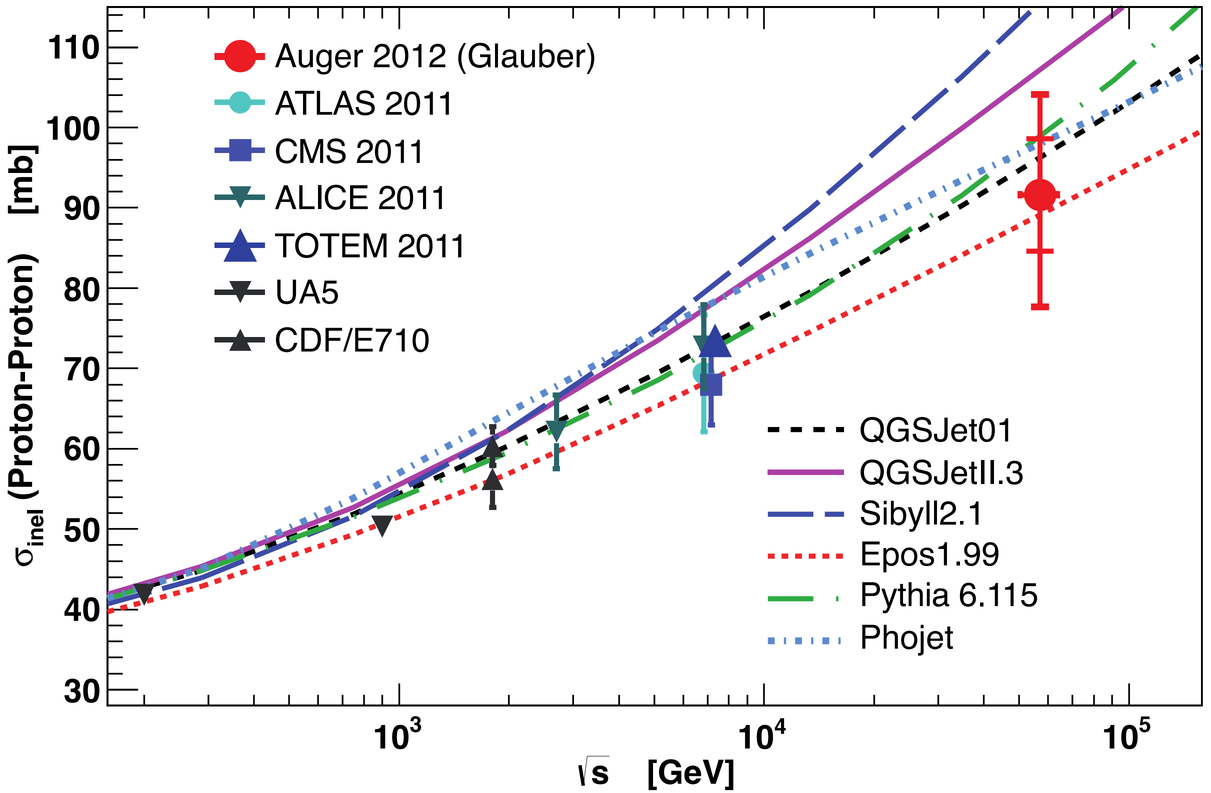
$$pp \to \gamma X$$

(LHCf Collab., Phys. Lett. B 703, 2011)

Re-tuning of models needed, size of effect still unclear, distributions for neutrons needed

Cosmic Rays and LHC: total cross section

pp inel. cross section at sqrt(s)=57 TeV



- Test Glauber model
- Tune EAS simulations

Neutrino interactions with Earth

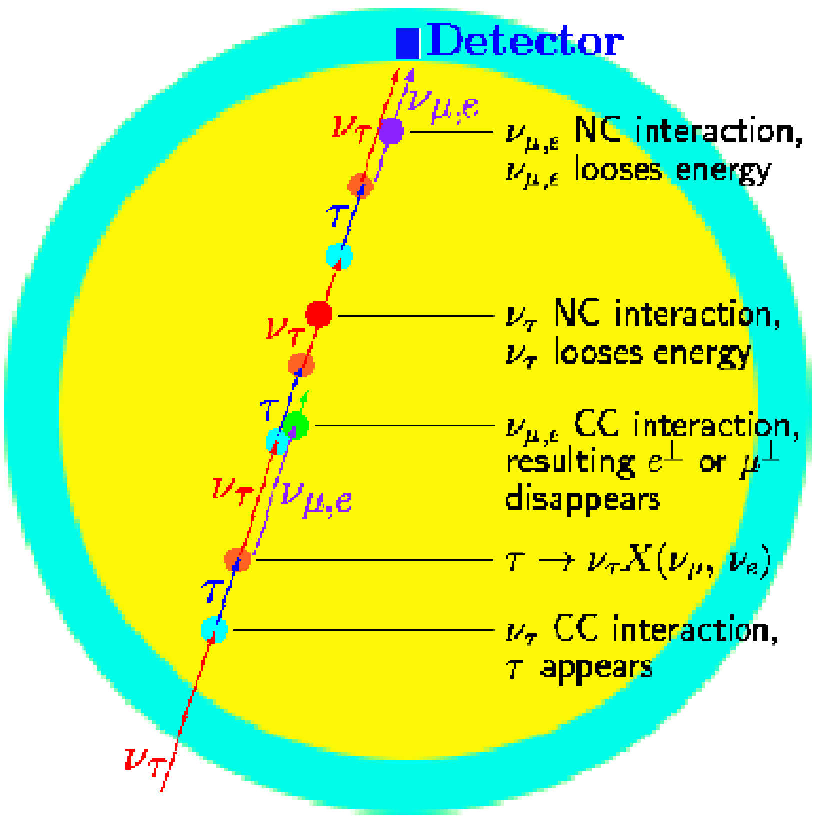
$\nu_\tau \rightarrow \tau \rightarrow \nu_\tau \rightarrow \ldots$

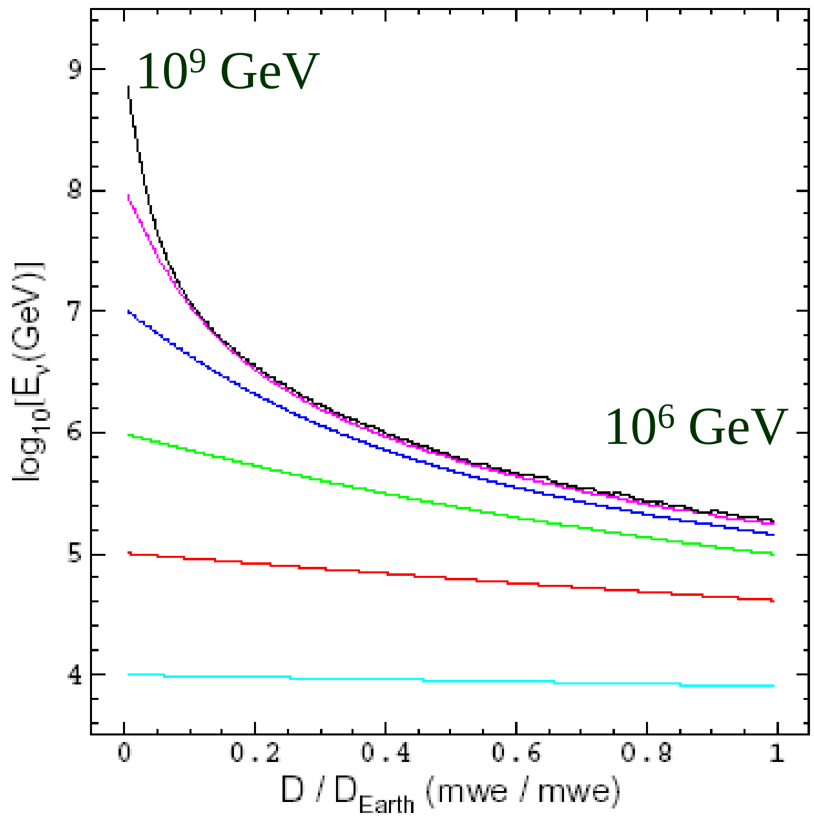
ν_τ energy degradation

$\sigma_\nu \nearrow E_\nu$

The Earth is opaque to ν_e ν_μ

Above $E_\tau \sim 10^7$ GeV: $L_{\tau int} < L_{\tau decay}$





Fraction of Earth diameter